Effect of Low-Pass Filtering and Re-Sampling on Spectral and Peak Ground Acceleration in Strong-Motion Records

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SUMMARY:
Strong-motion acceleration records are usually processed and released to the users as corrected acceleration, velocity and displacement. Correction is applied to both low- and high-frequency ends of the spectrum where signal-to-noise ratios are relatively low. I am considering effects of correction procedures on a 5% damped response spectra (RS). Common belief is that correction procedures mostly affect the low-frequency, but not the high-frequency part of the RS important for the earthquake response of non-structural elements and part of seismic hazard assessment for critical facilities. I am demonstrating that the use of traditional low-pass filtering combined with re-sampling (decimation) of recorded acceleration may significantly lower high-frequency SA values sometimes starting from frequencies as low as 6-8 Hz. This effect is especially significant for the largest recorded high-frequency ground motions, such as a number of the M_W 6.7 Northridge 1994, M6.3 2011 Christchurch, New Zealand and Mw 9.0 2011 Tohoku earthquake recordings.

Keywords: Corrected and uncorrected PGA, High-frequency Response Spectra, Low-pass filtering

1. STRONG-MOTION DATA PROCESSING

Strong motion data processed and released by the two main organizations collecting and processing data in the United States the United States Geological Survey (USGS) and the California Geological Survey (CGS) can be accessed at the website http://www.strongmotioncenter.org/. If one uses "Download Table" button the following two columns appear: PGAv1 and PGAv2. A header of a strong motion data file processed by the California Geological Survey (CGS) contains both values: uncorrected and corrected PGAs. What is and why PGAv1 and PGAv2 are different? Since not all users are familiar with those abbreviations and their meaning it may be useful to clarify those differences, and discuss a few related issues.

PGAv1 is a peak ground acceleration from the Volume 1 data, or uncorrected acceleration. PGAv2 is a peak ground acceleration from the Volume 2 data, or corrected acceleration. This terminology was first introduced in Caltech data processing (Trifunac, 1971; Trifunac and Lee, 1978, 1979). The values in those two columns are usually but not always very close.

Volume 1 is a digitized film record or a digitally recorded acceleration. The corrections made to it, are minimal consisting of a baseline shift removal and applying sensitivity factor to bring the amplitudes to the acceleration values in gravity g units. For film (e.g., SMA-1) recording PGAv1 corresponds to the maximum acceleration typically from a non-constant time step. Each data point in an uncorrected record file had two values: time and amplitude. This system was introduced by Caltech at the beginning of 1970s (Trifunac 1971, 1972; Trifunac and Lee 1978, 1979) and used in digitization of strong motion records in the United States. In the former Soviet Union digitization system used uniform time step in mm, corresponding to the uniform digitization time step in seconds. For example, digitization time step of the M_W 7.0 Gazli, Uzbekistan 1976 record was constant 0.00657 sec (Shteinberg et al., 1980).

PGAv2 corresponds to the maximum acceleration of the corrected or processed acceleration and represents the maximum of the record with a constant time step. It is usually, but not always consistent with integrated velocity and displacement. This value is a result of data processing that usually included interpolation to the constant digitization time step, instrument correction, baseline correction, application of a high and low-pass filters and decimation. Evidently, there is a difference between maximum uncorrected (PGAv1) and corrected (PGAv2) accelerations. There are a number of different procedures of data processing (correction) resulting in different values of PGAv2 (Trifunac, 1971, 1972; Graizer, 1979; Converse and Brady, 1992; Shakal et al., 2003: Chiou et al., 2008). In this paper we will concentrate on the high-frequency part of acceleration spectra and low-pass filtering affecting amplitude of the corrected acceleration recording. Table 1 presents a summary of the processing affecting the high-frequency component of corrected acceleration, and summarizes different data processing procedures commonly used in the United States. As can be seen from the Table 1 the procedures used by different organizations vary, and consequently may result in different amplitudes of the so-called corrected acceleration.

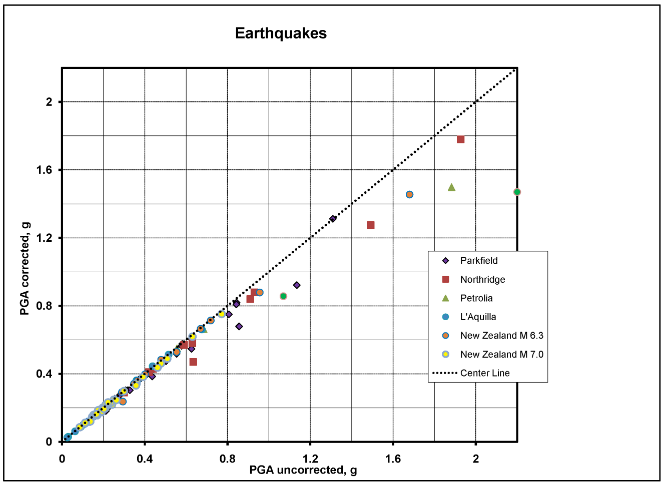

Figure 1.1. Examples of corrected and uncorrected PGA.

For users of strong-motion data the most important aspect is how significant is the difference between the uncorrected and corrected values. The general belief in the earthquake engineering community is that those differences are insignificant and don't exceed a few percent. Figure 1.1 and Table 2 demonstrate the comparison of a number of published PGAv1-PGAv2 values for recent strong earthquakes recorded by analog and digital instruments. The differences between PGAv1 and PGAv2 are usually not more than couple percents, but can be large in a number of cases shown in Table 2. Besides confusion between data users not familiar with details of this transformation it also raises the question of what should be called PGA: corrected or uncorrected value. For Northridge, Parkfield, Petrolia and the two recent New Zealand earthquakes the differences between the amplitudes of corrected and uncorrected data in a few cases are significant, and reach 25% (M_W 6.7 1994 Northridge earthquake, station Los Angeles - UCLA Grounds, Fig. 3.1b) and 33% (M_W 6.3 2011 Christchurch earthquake, New Zealand, station Heathcote Valley Primary School, vertical channel, Fig. 3.2b).

The typical steps in strong-motion data processing after digitization that result in differences between PGAv1 and PGAv2 are described in Shakal et al., (2003):

1. The raw digitized data points are converted to acceleration units using the sensitivity constant of the accelerometer. At least a first-order base-line correction is performed, to make the data zero-mean. The results of this step are usually denoted as Volume 1, and released as raw data product. Actually, it is more appropriate to call Volume 1 data "minimally corrected" instead of "uncorrected" since at least two processing steps were already applied to the discrete acceleration signal.

2. Instrument correction. As a first approximation, the response of an accelerometer to input ground motion can be described as:

$$\ddot{y}(t) + 2\omega_n D_n \dot{y}(t) + \omega_n^2 y(t) = -S_0 \ddot{x}(t) \tag{1}$$

where $y(t)$ is the recorded response of the instrument, ω_n and D_n are the natural circular frequency ($\omega_n = 2\pi f_n$) and fraction of critical damping of the oscillator, $\ddot{x}(t)$ is the translational ground motion acceleration, and S_0 is the gain factor. In the frequency domain the response of an accelerometer can be written

$$G_a(\omega) = S_0 \Big/ \sqrt{\left[1-(\omega/\omega_n)^2\right]^2 + 4D_n^2(\omega/\omega_n)^2} \qquad (2)$$

The base-line adjusted data can be corrected for instrument response using a simple finite-difference operator in time domain. In frequency domain processing, the finite-difference process is replaced by dividing the spectrum of recorded signal by the instrument's transfer function (2) (Figure 1.2 a, b). At high-frequencies instrument correction $(1/G_a(\omega))$ is equivalent to multiplication of the signal by ω^2.

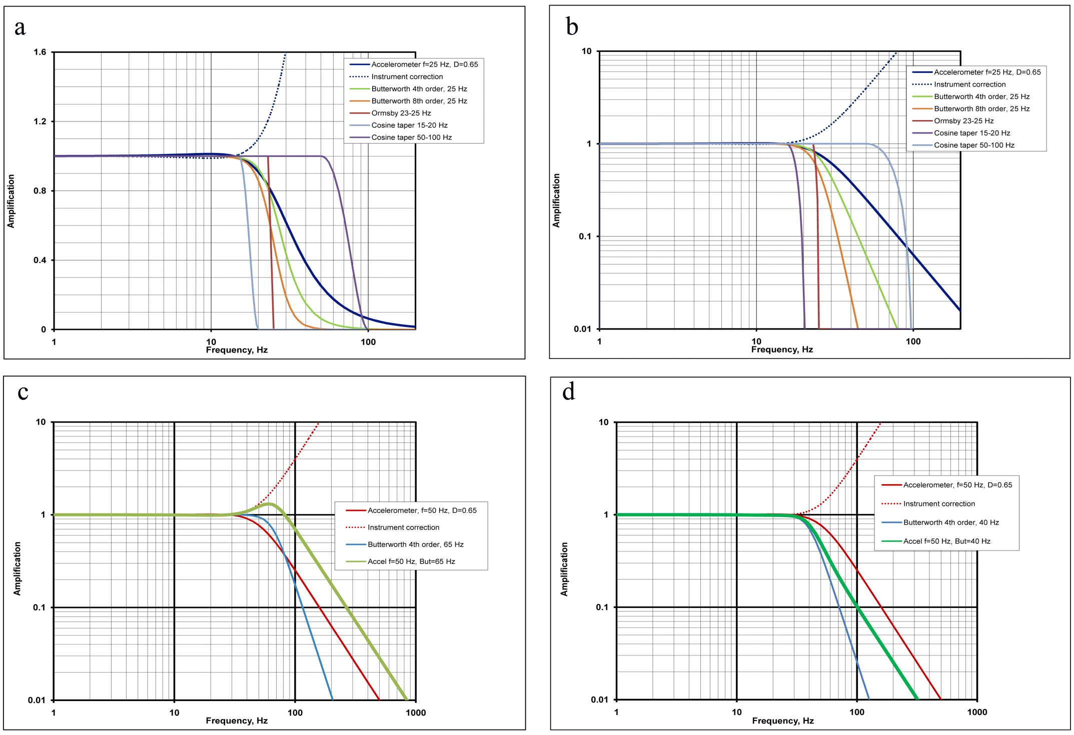

Figure 1.2. Effect of instrument correction and low-pass filtering: a – instrument correction and different type of low-pass filters (log-lin scale); b – same as "a" with log-log scale; c – combined effect of instrument correction and low-pass filter with filter's frequency higher than the natural frequency of the instrument; d – same as "c", but with filter's frequency lower than the natural frequency of the instrument.

3. High frequency filtering after instrument correction is usually applied to remove high frequency noise. In the Caltech, University of Southern California (USC) and CGS processing, an Ormsby filter with a corner frequency at 23 Hz and a termination frequency at 25 Hz was applied (Trifunac, 1972; Trifunac and Lee, 1978, 1979) (Figure 1.2 a, b). For modern digital records, CGS uses a Butterworth filter with a corner frequency near 80% of the final sampling rate (usually, 100 samples/sec) and a 4th order decay (Shakal et al., 2003). USGS is using cosine taper filter (similar to Ormsby, but with smooth ends) (Converse and Brady, 1992). After filtering, the data are decimated to the final sample rate. For example, the rate is 50 points/second in the Caltech/USC and CGS analog data; CGS usually distributes data at 100 samples/sec rate for data recorded digitally. The transfer function of a *k*-order Butterworth low-pass filter is given by

$$G_B(\omega) = G_0 \Big/ \sqrt{1+(\omega/\omega_c)^{2k}} \qquad (3)$$

where G_0 is the filter's gain factor and ω_c is the filter's corner frequency.

4. Integration and Long Period Filtering. Velocity and displacement are obtained by numerically integrating the acceleration and filtered using the same low-frequency filter (in Caltech data processing, Trifunac, 1971; Trifunac and Lee, 1978). There are other procedures for calculation of velocity and displacement currently used (e.g., Converse and Brady, 1992; Graizer, 1979), but this article considers the effect of high-frequency correction and filtering on acceleration.

2. EFFECTS OF HIGH-FREQUENCY FILTERING

High-pass filtering significantly affects integrated velocity and displacement, but usually not as much acceleration. In this paper we are considering effects of the low-pass filtering. Theoretically, spectral amplitude of the instrument- corrected acceleration should be higher than that of the uncorrected one, because of the frequency response characteristics of an accelerometer de-amplifying the input signal at frequencies higher than the natural frequency of the sensor ω_n (Equations (2) and Figure 1.2). However, after interpolation, filtering and decimation, corrected accelerations are usually lower than the uncorrected ones.

Combination of the instrument correction with high-frequency filtering using Butterworth filter is same as applying filter $F(\omega)$ with frequency response

$$F(\omega)=\frac{G_B(\omega)}{G_a(\omega)}=\frac{G_0}{S_0}\sqrt{\frac{\left[1-(\omega/\omega_n)^2\right]^2+4D_n^2(\omega/\omega_n)^2}{1+(\omega/\omega_c)^{2k}}} \qquad \underset{\omega\to\infty}{F(\omega)}\sim 1/\omega^{k-2} \tag{4}$$

For the commonly used Butterworth of the 4th order filter the final roll-off of the transfer function $F(\omega)$ is ($1/\omega^2$), and for the 5th order filter it is ($1/\omega^3$).

Depending upon the natural frequency of the instrument (ω_n) and the filter's corner frequency (ω_c) there are three possible situations:

1. The cut-off of the low-frequency filter is higher than that of the natural frequency of the accelerometer $\omega_c > \omega_n$ (Figure 1.2 c). In the example shown in Figure 1.2c ($f_n = 50Hz,\ \ f_c = 65Hz$) in the frequency range from 0 up to ~35 Hz instrument correction combined with filtering does not produce any effect on the signal; results in the amplification of the recorded (uncorrected) signal in the frequency range of approximately 35 up to 80 Hz; and the final decay of the inverse and low-pass filter is $(1/\omega^2)$. The corner frequency and the slope of the Butterworth filter is chosen based on the noise level in the high-frequency part of signal's Fourier spectrum. In this case in the limited frequency range the total inverse filter (instrument correction + Butterworth) produces amplification of acceleration, and later decay of the order of $(1/\omega^2)$ (Equation 4) with practically no change to the signal for frequencies lower than ω_n.

2. The cut-off the frequency of the low-pass filter is the same or lower than that of the natural frequency of an accelerometer $\omega_c \le \omega_n$ (Figure 1.2d $f_n = 50Hz,\ \ f_c = 40Hz$). In this second case, used for example by the CGS, instrument correction is immediately compensated by the faster slope of the Butterworth filter, and basically only slows the roll-off of the low-pass filter. In the examples shown in Figure 1.2 c, d the final roll-off of the low-pass filter multiplied by the Butterworth of the 4-th order is $(1/\omega^2)$. It is not clear what is the reason to perform instrument correction, since correction and filtering can simply be replaced by low-pass filtering of lower order (with no instrument correction).

3. The instrument correction is not done. USGS takes this approach in its processing of digital recordings (Chris Stephens, USGS, personal communication), and typically applies cosine taper filter with transition from 50 to 100 Hz for digital and 15 to 20 Hz for film records.

As can be seen from comparison of the 4-poles Butterworth with the Ormsby or cosine type filter (Figure 1.2 a, b), the first one is much more “smooth” than the two others. Even the higher order (e.g., 8-poles) Butterworth is still more smooth and in contrast to Ormsby and cosine taper never goes to zero. Both Ormsby and cosine taper low-pass filters reject (filter out) completely frequency content of the signal higher than the certain level. As stated by Butterworth (1930) “An ideal electrical filter should not only completely reject the unwanted frequencies but should also have uniform sensitivity for the wanted frequencies."

Re-sampling of time series from 200 to 100 or 50 samples/sec affects the upper limit of the Fourier spectra calculation, since Nyquist frequency goes down from 100 Hz to 50 or even 25 Hz and results in the limitations in further use of the data. Besides that, re-sampling (decimation) often results in “missing” the highest peak values.

3. EXAMPLES

In many cases like for example for the digital record of Northridge earthquake at the Los Angeles – University Hospital Grounds (CGS No. 24605) low-pass filtering was performed in a way that there was almost no visual differences between uncorrected (PGA=0.494 g) and Pacific Earthquake Engineering Research (PEER) Center (PGA=0.493 g) and CGS (PGA=0.492 g) corrected records. Both CGS and PEER used similar cut-off frequencies of about 46-50 Hz in their processing, and re-sampled record to 100 samples/sec that put limitations of 50 Hz on Fourier spectrum calculations. There are practically no differences between uncorrected and corrected amplitudes of SA at high-frequencies.

Similarly to the previously described case, CGS processing of the digital recording of the M_W 6.0 Parkfield 2004 earthquake at the Parkfield - Cholame 5W (CGS No. 36227) station resulted in no visible difference between uncorrected and corrected time series, with Fourier spectra different in the low and high-frequency areas. CGS applied Butterworth filter of the 4th order with the cut-off frequency of 40 Hz (this cut-off frequency is used by CGS for all digital recordings). There are no visible differences between the uncorrected and corrected SAs at all frequencies.

Figure 3.1 demonstrates an example of the CGS and PEER processing of an analog film SMA-1 record of the Northridge earthquake at the station Los Angeles – UCLA Grounds. As can be seen from the Figure 3.1b there is a significant difference between the uncorrected (0.634 g) and corrected (0.474 g) PGAs, with minimal differences between CGS and PEER corrections. Both CGS and PEER used similar cut-off frequencies of about 23-25 Hz in their processing, but different types of filters: CGS – Ormsby, and PEER - Butterworth. Figure 3.1d demonstrates significant differences in uncorrected and corrected SA values at frequencies higher than 6 Hz.

Figure 3.2 demonstrate an example of processing of the strongest record of the recent M_W 6.3 Christchurch 2011 New Zealand earthquake. The strong motion data were recorded by digital accelerographs CUSP-3 (http://csi.net.nz/cusp3b.html) with sampling rate of 200 samples/sec. They were processed following the 1970s Caltech procedure, low-pass filtered and re-sampled to 50 samples/sec by the GeoNet New Zealand strong motion network. The GeoNet website (http://www.geonet.org.nz/resources/basic-data/strong-motion-data/) and headers of the corrected record files do not provide information about the actual natural frequencies of accelerometers that can be 40 or 80 Hz according to the sensor’s specifications. Comparisons of the uncorrected and corrected data demonstrate huge differences in the PGA values and amplitudes of response spectra at high frequencies. Based on the noise in the Fourier spectra of uncorrected records, I don’t see any reason to apply such a low cut-off frequency of the low-pass filter. My choice will be 50-80 Hz cut-off frequencies. A combination of re-sampling at 50 samples/sec with filtering results in a significant loss of amplitude and high-frequency content. It also significantly impacts response spectrum.

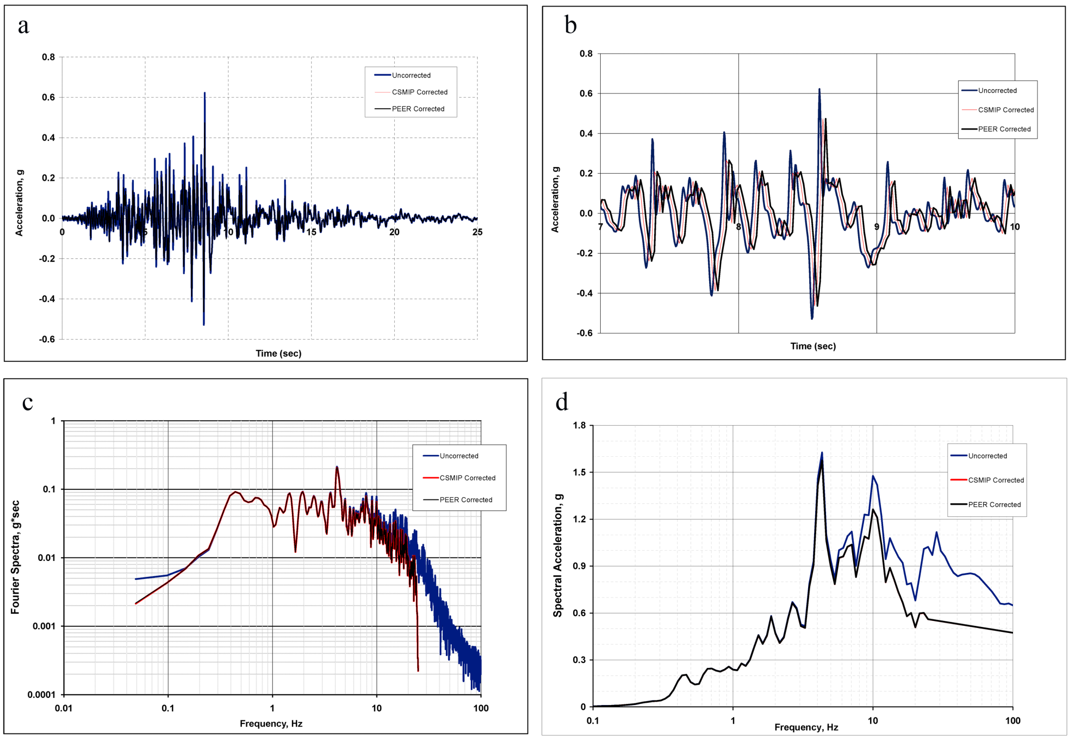

Figure 3.1. Record of the M_W 6.7 Northridge earthquake at Los Angeles – UCLA Grounds CGS station No. 24688: a, b – uncorrected and corrected acceleration (corrected record is artificially shifted in time relatively to the uncorrected one to make their comparison visible); c – Fourier spectra of uncorrected and corrected acceleration; d – 5% damped response spectra of uncorrected and corrected acceleration.

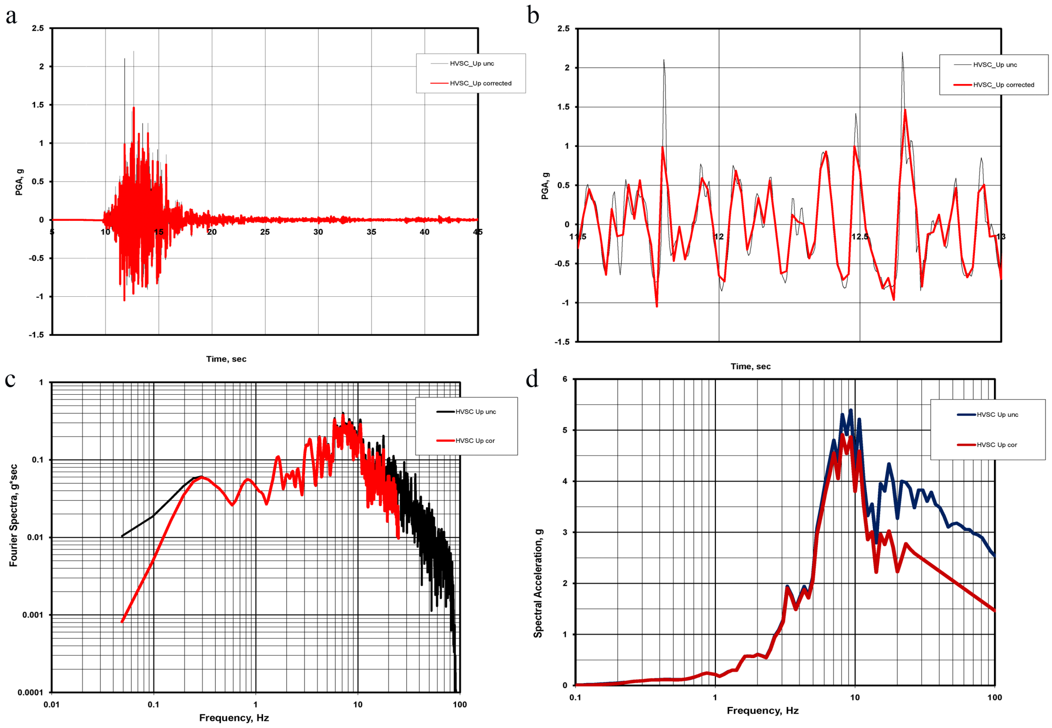

Figure 3.2. Record of the M_W 6.3 Christchurch, New Zealand earthquake at Heathcote Valley Primary School (HVSC) station, Up-component: a, b, c, d same as in Figure 3.1.

Figure 3.3 demonstrates alternative method of data processing of one the records of this event (Heathcote Valley Primary School (HVSC), Up-component). I used the program COFDVA (developed in 1980s and last modified in 1992, Graizer, 1979). Processed data have a bandwidth of 0.1 to 40 Hz with a relatively smooth slopes of the low (f^2) and high-pass filters ($1/f^2$). No re-sampling was done, and the original sampling rate of 200 samples/sec was preserved. Figure 3.3b shows that the differences between corrected and uncorrected accelerations are much lower (2.07 vs. 2.20 g) compared to the data processing performed by the New Zealand GeoNet (1.47 vs. 2.20 g; Figure 3.2b). Difference between corrected and uncorrected SA is also much smaller (Figures 3.2d and 3.3d).

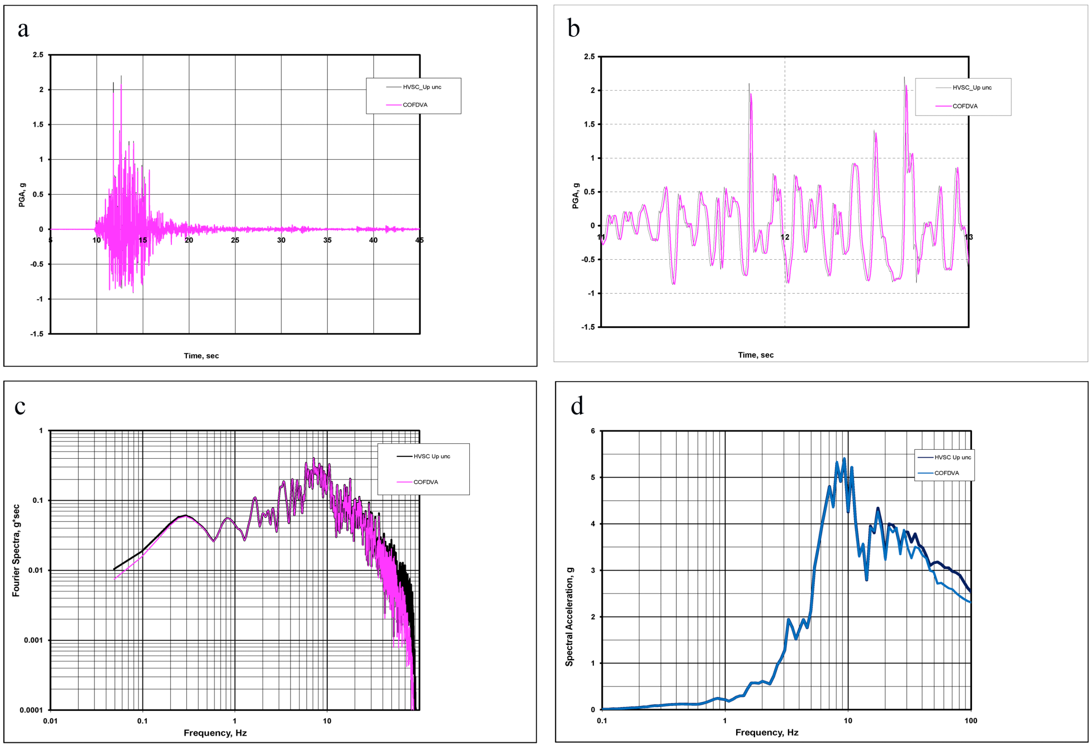

Figure 3.3. Record of the M_W 6.3 Christchurch, New Zealand earthquake at Heathcote Valley Primary School (HVSC), Up-component, processed with computer code COFDVA and filter's frequency of 40 Hz: a, b, c, d same as in Figure 3.1.

Comparison of the uncorrected and corrected records of the M_W 9.0 2011 Tohoku, Japan earthquake recorded at the four K-NET (http://www.k-net.bosai.go.jp/) stations is shown in Table 2. The preliminary data processing performed by Kalkan (personal communication, March 2011) resulted in the decrease of PGA from 2.75 g to 2.47 g (10%) and visible decrease of the high-frequency component of the response spectrum for the MYG004 station. The records were sampled at the 100 samples/sec rate.

Shown examples demonstrate that use of the pre-defined fixed high-frequency cut-off filter may result in filtering out useful information not contaminated by noise, or sometimes not filtering out noisy frequencies. I don't recommend using a pre-defined high-frequency cut-off filter, but choosing it based on the noise level. This approach is used in PEER strong-motion data processing (Chiou et al., 2008), Next Generation Attenuation for Eastern US (NGA-East) project (Cramer, personal communication) and is also recommended by Douglas and Boore (2011).

The fact that the record was low-pass filtered with certain frequency does not actually limit its usability to the same frequency. If the filtering was done properly using a "smooth" Butterworth type filter there is nothing wrong with using this record beyond the filter's cut-off frequency. Filtering lower or even removes completely "noisy" frequencies. In many cases the headers of the processed files do not contain the information about both high- and low-pass filter corners, but only time step and units (e.g., PEER processed files which provide information about filtering in a separate table). The high-frequency limitation comes from the sampling rate, which is usually 50 samples/sec for analog records, and 100 or 200 samples/sec for digital records, resulting in maximum frequencies of 25, 50 or 100 Hz. Digitized signal can be re-sampled to the higher sampling rate (e.g., from 100 to 200 samples/sec) using interpolation technique, but it is known to create aliasing and can produce erroneous results.

4. CONCLUSIONS

The two different types of filtering that are used for strong-motion data processing: "truncation" type like Ormsby or Cosine taper completely filter out frequencies higher than certain value; and the smooth type of filters, like Butterworth of the 4^{th} or 5^{th} order bring down but do not completely eliminate noisy part of the frequency band. In the second case the slope of the Fourier spectrum of the record at noisy frequencies may continue decaying with the same slope as at the trusted part of the record. The first type of filters create truncated signal (with no frequencies higher than the termination frequency in the spectrum). The second smooth type of filters decreases the signal in the noisy area. In the best case it extrapolates signal behavior based on the signal behavior in the trusted area. I prefer using smooth type of filters like Butterworth. The purpose of this paper is not to compare and judge which method of high-frequency correction of strong-motion records is better, but to bring to the attention of strong-motion data users the following facts:

1. High-frequency correction in combination with decimation and other steps involved in data processing result in a value of PGA different from that of the recorded uncorrected PGA value. In some cases of especially large accelerations those differences may be significant and can exceed 20%.
2. Different procedures of records correction used by the organizations distributing strong motion data result in different values of corrected PGA. This also results in differences in response spectra values in the frequency range from as low as 6-8 up to 100 Hz (PGA) being lower than the uncorrected recorded ones.
3. There is a clear need to process and distribute strong motion data at least at the 200 samples/second rate to be consistent with the current practice in earthquake engineering. High-frequency component of the spectrum is important for the earthquake response of non-structural elements, electrical equipment and piping in engineering applications, and is part of seismic hazard assessment for nuclear power plants and other critical facilities (U.S. Nuclear Regulatory Commission, 2007).

There is only one uncorrected PGA and potentially multiple corrected PGA values depending upon the processing procedure. Considering that, I recommend that when data processing is performed special attention be paid to the comparison of the uncorrected PGA value with the corrected one avoiding low-pass "over-filtering" of strong-motion data that can result in a loss of critical information. The extreme example of this is processing of the M6.3 Christchurch digitally recorded earthquake data using an old procedure developed for processing film records.

From my point of view, there is a certain level of disconnect between some of the strong-motion data processing organizations and earthquake engineering community of data users, with strong-motion data been processed in a way that they can only be used up to the frequencies of 50 or even 25 Hz. It leaves a gap between 25 or 50 Hz and PGA assigned to the value of 100 Hz. Simple re-sampling of the signal with higher sampling rate (e.g., from 100 to 200 samples/sec) creates aliasing and can produce erroneous results. There is a clear need in releasing all recent digitally recorded strong-motion data with a sampling rate of 200 samples/sec to satisfy the needs of earthquake engineering including design of critical facilities. It is especially important considering that it does not require any improvements in technology.

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DISCLAIMER
Any opinions, findings and conclusions expressed in this paper are those of the author and do not necessarily reflect the views of the United States Nuclear Regulatory Commission.

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http://peer.berkeley.edu/peer_ground_motion_database Last accessed on April 18, 2011.

Table 1. High-frequency correction and filtering

Data provider	Instrument correction	Type of Low-pass filter	Filter frequency, Corner-Termination	Choice of filter
Caltech, USC and CGS till 1999	Applied	Ormsby	Pre-fixed to 23-25 Hz	Same for all three channels
CGS since 1999	Applied	Butterworth of 4-th order	23.6 Hz for SMA, 40 Hz for digitals	Same for all three channels
USGS	Applied to analog records	Cosine taper	Pre-fixed to 15-20 Hz	Same for all three channels
USGS	Not applied to digital records	Cosine taper	Usually prefixed to 50 Hz, and/or applied based on noise level	Same for all three channels
PEER	Applied	Butterworth of 4-th order	Chosen based on noise in FAS	Each channel separately
NGA-East[1]	Applied	Butterworth of 4-th order	Chosen based on noise in FAS	Same for all three channels

[1] - NGA-East – Next Generation Attenuation Relationships for Eastern United States project.

Table 2. Example comparisons of uncorrected and corrected PGA values

Earthquake	Station	Uncor-rected, g	Correc-ted, g	% difference	Instru-ment	Processing
Gazli Uzbekistan 1976	Karakyr	1.36	1.25	8.1	SSRZ[1]	PEER
Parkfield 2004	Parkfield – Fault Zone 11	1.135	0.922	18.8	SMA-1	CGS
Parkfield 2004	Parkfield - Gold Hill 3W	0.856	0.679	20.7	SMA-1	CGS
Parkfield 2004	Parkfield - Cholame 3E	0.807	0.75	7.1	SMA-1	CGS
Parkfield 2004	Parkfield – Stone Corral 1E	0.843	0.809	4.0	SMA-1	CGS
Parkfield 2004	Parkfield - Cholame 2W (Sta 2)	0.629	0.605	3.8	SMA-1	CGS
Parkfield 2004	Parkfield - Fault Zone 8	0.626	0.547	12.6	SMA-1	CGS
Northridge 1994	Tarzana - Cedar Hill Nursery A	1.927	1.78	7.6	SMA-1	CGS
Northridge 1994	Santa Monica - City Hall Grnds	0.93	0.88	5.4	SMA-1	CGS
Northridge 1994	Sylmar - 6-st. Co Hospital	0.91	0.84	7.7	SMA-1	CGS
Northridge 1994	Los Angeles - UCLA Grnds	0.634	0.47	25.9	SMA-1	CGS
Northridge 1994	Newhall – County Fire Sta.	0.63	0.58	7.9	SMA-1	CGS
New Zealand M6.3, 2011	Heathcote Valley School	1.68 2.20	1.455 1.47	13.4 (H1) 33.2 (Up)	CUSP-3	GeoNet[2]
New Zealand M6.3, 2011	Lyttelton Port Company	0.956	0.879	8.1	CUSP-3	GeoNet
New Zealand M6.3, 2011	Christchurch Botanic Garden	0.554	0.529	4.5	CUSP-3	GeoNet
New Zealand M6.3, 2011	Hulverstone Pump Sta	0.294	0.237	19.4	CUSP-3	GeoNet
New Zealand M7.0, 2010	Heathcote Primary Schl.	0.631	0.619	1.9	CUSP-3	GeoNet
New Zealand M7.0, 2010	Darfield High School	0.509	0.489	3.9	CUSP-3	GeoNet
New Zealand M7.0, 2010	Hororata School	0.478	0.461	3.6	CUSP-3	GeoNet
New Zealand M7.0, 2010	Lincoln Crop & Food Research	0.462	.437	5.4	CUSP-3	GeoNet
New Zealand M7.0, 2010	Kaiapoi North School	0.361	0.344	4.7	CUSP-3	GeoNet
New Zealand M7.0, 2010	Lyttelton Port Company	0.358	0.332	7.3	CUSP-3	GeoNet
Tohoku, Japan, M9.0, 2011	MYG004	2.755	2.472	10.3	Not known	Preliminary
Tohoku, Japan, M9.0, 2011	IBR003	1.631	1.488	8.8	Not known	Preliminary
Tohoku, Japan, M9.0, 2011	MYG0013	1.548	1.384	10.6	Not known	Preliminary
Tohoku, Japan, M9.0, 2011	IBR013	1.383	1.298	6.1	Not known	Preliminary

1 SSRZ is a film accelerograph build in the Former Soviet Union with natural frequency of ~ 20 Hz and damping of ~ 0.6 (similar to the SMA-1).

2 - GeoNet is New Zealand network that includes strong motion stations.