Consortium of Organizations for
Strong-Motion Observation Systems

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Guidelines and Recommendations for Strong-Motion Record Processing and Commentary

Strong-Motion Record Processing
Working Group

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Consortium of Organizations for
Strong-Motion Observation Systems

and the

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COSMOS Working Group on Strong-Motion Record Processing

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Guidelines and Recommendations

INTRODUCTION

Uniform standards for processing are not achievable at this time because of a variety of issues. That said, processing agencies are encouraged to use these recommended processing guidelines to provide a readily accessible, clear, and thorough description of the processing procedure used by their agency to provide a readily accessible, clear, and thorough description of the processing procedure used by their agency. The processing procedures that are used should be clearly documented so that the results can be reproduced. The user should be able to determine from the data and its metadata what procedures have been applied.

In general, the expression 'corrected data' should be avoided, in favor of 'processed data'. In these guidelines, Vol. 1 means the unprocessed record, with no filtering or instrument correction procedures applied, though deglitching and other basic signal conditioning steps may have been performed on the raw data. Also, a 'record' here means all of the channels recording the response of the station or structure.

The guidelines and recommendations presented below represent a consensus, which was developed in the discussion session of the *COSMOS Workshop on Strong-Motion Record Processing* [1]. This important international workshop, which provided the technical foundation for these guidelines and recommendations, convened representatives of strong-motion observation networks located in thirteen countries together with strong-motion record analysts, researchers, and practitioners. Workshop participants reviewed current strong-motion record processing practices and considered specific record processing requirements for particular earthquake engineering applications. Following these reviews, the guidelines and recommendations presented in the next section were developed by the COSMOS Strong-Motion Records Processing Working Group. Details about current strong-motion record processing international practice can be found in the workshop proceedings.

Appendix A of this guideline contains commentary on use of the guidance and recommendations. The commentary is taken from Boore and Bommer [2].

SPECIFIC GUIDANCE

Compatible versus Incompatible Processed Data Products

Insofar as possible, data products released should be 'compatible' –that is, released acceleration should be able to be used (by a general user) to calculate velocity, displacement, and spectra that match those released with the acceleration. Cases where this is not done should be clearly noted by the releasing agency, through comments and/or reference to a tutorial document, because in many engineering analysis programs, only a single time series typically is used for an analysis run, making the compatibility issue more important.

FILTERING BY RECORD VERSUS FILTERING BY CHANNEL

Currently, records are released by agencies like the U.S Geological Survey (USGS) and California Geological Survey (CGS) with all channels filtered with the same filter corner. In many cases, it is also beneficial for the records to be released with, for example, all horizontals filtered the same, or every channel filtered separately. If included, the set of individually filtered channels should be clearly indicated as an alternate set. Clear documentation for the user is important so that the difference is understood. An alternate way to address this need may be the release of the unprocessed data, so that a knowledgeable user can process the records as desired. Although this guideline may be applied in general, this workshop focused on ground response as opposed to structural records.

Release of Unprocessed Data

The ability of investigators to work with unprocessed data is critical for research and progress in understanding noise characteristics, data offsets, and other issues. COSMOS member agencies are encouraged to release unprocessed (Vol. 1) data for research and, upon special request, to provide raw data as well. Organizations in a position to process data for open release are requested not to process for release data already released by the source network because of the potential confusion multiple releases of processed records would cause. It is incumbent upon anyone releasing reprocessed data to be very clear what the differences are relative to the original release.

Usable Data Bandwidth

The usable data bandwidth should be documented and distributed with processed data in a manner clear to the data user. Recommendations against use of the data outside of this bandwidth should be included with the data file and in an expanded form in documents on the agency's (or another) website. Response spectral values should only be provided within the Usable Data Bandwidth defined by the processing group [3]. This limitation should be clearly documented for the user.

Acausal Filters

In general, acausal filters should be used unless there are special factors involved. This has been found to be particularly important if the data will be used to generate inelastic response spectra. Any usage of causal filters should be clearly documented in the information and comments accompanying the data. If causal filters are used (e.g., in real-time applications), it is important that the same filter corner be used for all components.

End Effects

In routine processing, one way to treat late-triggered records is by tapering of the records before processing. A raised cosine applied to the first and last few percent (e.g., 5) of the record length is a reasonable taper. Late-triggered records and records with permanent offset should only be tapered with care; for these cases a more complex (or no) tapering may be appropriate. Any tapering done should be documented. In addition to tapering, another approach is to trim the record at the location of the first zero-crossing in the record.

Processing of late-triggered records (i.e., records with little or no recorded data before the high amplitude motion) is quite uncertain, and more than normally dependent on details of the procedures used in processing. In general, it is recommended that late-triggered records not be used if otherwise equivalent records are available.

Time Domain versus Frequency Domain

In general, excluding base line corrections, careful processing with time domain and frequency domain procedures yields comparable results.

Metadata

Metadata (i.e., information about the data) should be provided with the data. To prevent confusion by users, the original metadata should be preserved in the data file. If other agencies reprocess or redistribute the data, they should indicate the data file as the original metadata. Modifications or additions to the metadata should also be clearly indicated in the metadata. A minimum set of parameters should be provided in the metadata. (The subset of the COSMOS format parameters (attached) is defined as 'critical'.)

High Frequencies

High frequencies can be important at hard rock sites and in areas of low attenuation. Data should be provided out to as high a frequency as allowed by the signal and noise. A sampling rate as high as feasible (e.g., 200 sps or higher) is important for good definition of the strong acceleration pulses. The anti-aliasing filter of the recorder should be consistent with the sample rate.

Instrument Correction

Complete information about the instrument response and any instrument correction performed should be documented with the data.

Sensor Offsets

Sensor offsets can be a significant issue with modern data. The presence of offsets should be checked as a part of determining whether routine processing can be applied (e.g., by removing a suitable reference level(s) and checking the velocity for trends, or equivalently checking for different DC acceleration levels at the start and end of a record). Offsets can be estimated by several techniques; the most successful at this time requires a case-by-case approach involving inspection of intermediate time series and/or spectra.

Selecting Long-Period Filter Period

In the absence of offsets (or after correction for them), the long-period filter corner selection should incorporate analysis of signal and noise. Using a ratio of recorded signal-to-noise of not less than 2 is recommended. This selected period should be reviewed in the time domain to verify that clearly unphysical velocity and displacement time series are not produced (when possible, considering similarity of displacements obtained for nearby stations is a recommended technique). Peak displacement is strongly dependent on the long-period filter corner. True permanent displacement may, in general, not be obtainable from triaxial strong-motion records alone.

Due to uncertainty in obtaining permanent displacement from accelerometers, networks are encouraged to include direct measurement of displacement (e.g., selective co-location of differential GPS instruments) in strong motion networks.

Processed Data Format

To increase convenience for data users and simplify data exchange with other networks, processing agencies are encouraged to release their processed data in the COSMOS format (www.cosmos-eq.org), or, alternatively, provide a conversion module at their website to convert files from their format to the COSMOS format.

REFERENCES

1. Shakal, A. F., D. M. Boore, B. S.-J. Chiou, W. D. Iwan, D. R. O'Connell, and J. Carl Stepp (2005). Proceedings: Workshop on Strong-Motion Record Processing, *COSMOS Publication No. CP-2004/01*, Richmond, CA.

2. Boore, D. M., and J. J. Bommer (2005). Processing of strong-motion accelerograms: needs, options and consequences, *J. Soil Dyn. Earthq. Engrg.,* 25(2): 93-115.

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APPENDIX A

COMMENTARY ON GUIDELINES AND RECOMMENDATIONS FOR PROCESSING STRONG-MOTION RECORDS

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This appendix provides commentary on the guidelines and illustrations of the guidelines. This commentary is based on the paper by Boore and Bommer [1], to which readers are referred for additional information and general background.

COMPATIBLE VERSUS INCOMPATIBLE PROCESSED DATA PRODUCTS

Insofar as possible, data products released should be 'compatible' –that is, released acceleration should be able to be used (by a general user) to calculate velocity, displacement, and spectra that match those released with the acceleration. Cases where this is not done should be clearly noted by the releasing agency, through comments and/or reference to a tutorial document.

Processed accelerograms are generally distributed as files of equally spaced samples of acceleration, velocity, and displacement, and these are often accompanied by the response spectra for various damping levels. Users are often troubled by the fact that if they integrate the acceleration time-history, the velocities and displacements that they obtain do not match those provided by data distributors. In addition to this, the response spectra calculated from the acceleration time-histories will often not match the response spectra provided by the distributor, at least, for example, in so much as the long-period displacements may not converge to the peak ground displacement. In such cases, the data can be described as incompatible [2] [3] [4]; compatible data mean that the velocity and displacement time-histories and the response spectra obtained from the accelerations will match those provided.

There are two different causes for incompatible data. One is the practice of filtering the accelerations and then integrating these to obtain velocities, to which another filter is applied in order to reduce noise that is still present in the record. The process is then repeated on the displacements [5] [6]. The problems arise because the effects of the filters applied to the velocity and/or displacement are not carried back to the acceleration, hence the results from integration of the acceleration no longer match the velocity and the displacement that have been filtered. Careful selection of the filter parameters–and if necessary combining the filter with a reference baseline adjustmen–and appropriate handling of zero pads should make such iterative filtering unnecessary and certainly the practice of applying multiple filters is one that is to be discouraged

Another cause for data incompatibility is the removal of the pads that are added for the application of the filter. This issue is controversial; some argue that the pads are artificial and, therefore, do not constitute part of the data and should be removed. The consequence of their removal, however, is to undermine the effect of the filter; this can result in offsets and trends in the baselines of the velocity and displacements obtained by integration (Figure 1). The removal of the pads also has an influence on the long-period response spectral ordinates (Figure 2). For this reason, it is recommended that when acausal filters are used, sufficient lengths of zero pads should be added to the records and these pads should not be stripped out from the filtered data [7].

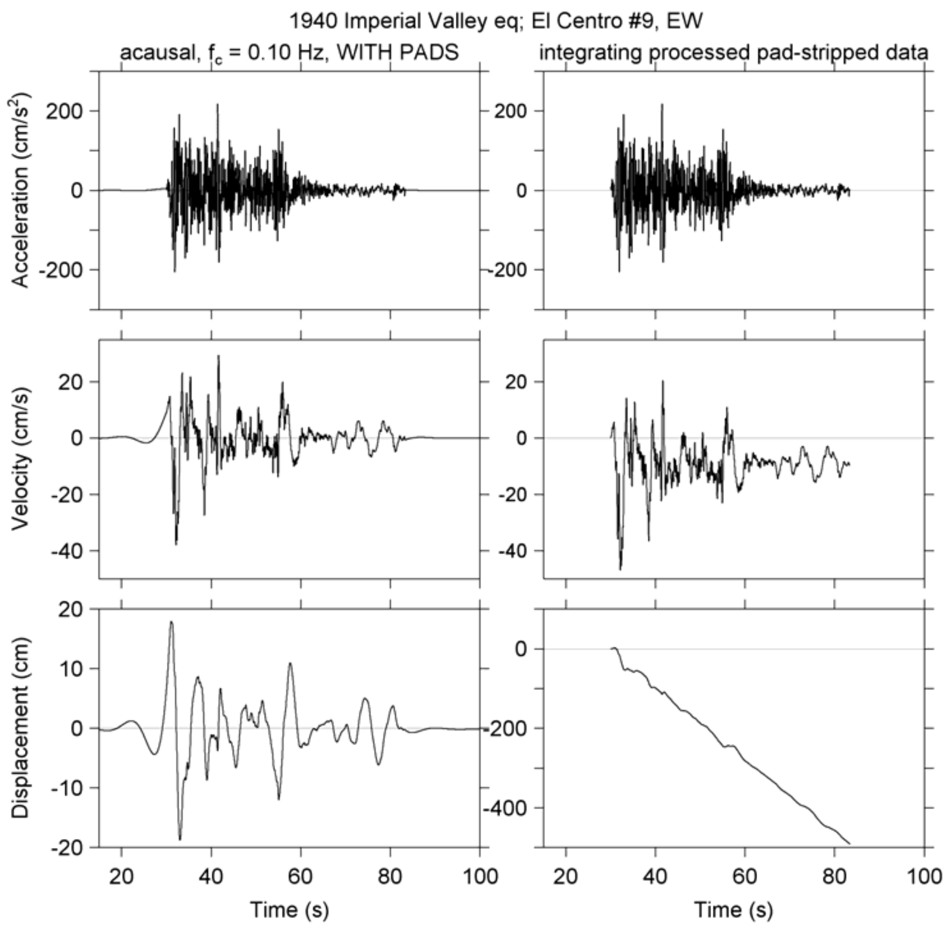

Figure 1. Accelerations, velocities, and displacements derived from the EW component accelerations recorded at El Centro station 9 during the 1940 Imperial Valley earthquake, illustrating the incompatibility of the processed data that does not include the padded portions of the processed data. The left panel shows results from padded and filtered data. In the right panel the padded portions have been removed from the processed acceleration time series (this corresponds to what several data agencies provide to the public) and the velocity and displacement have been obtained by integration of this pad-stripped data, assuming zero initial conditions. This is a particularly egregious example, but many records share the general features shown here. The unprocessed data are from Seekins et al. [8].

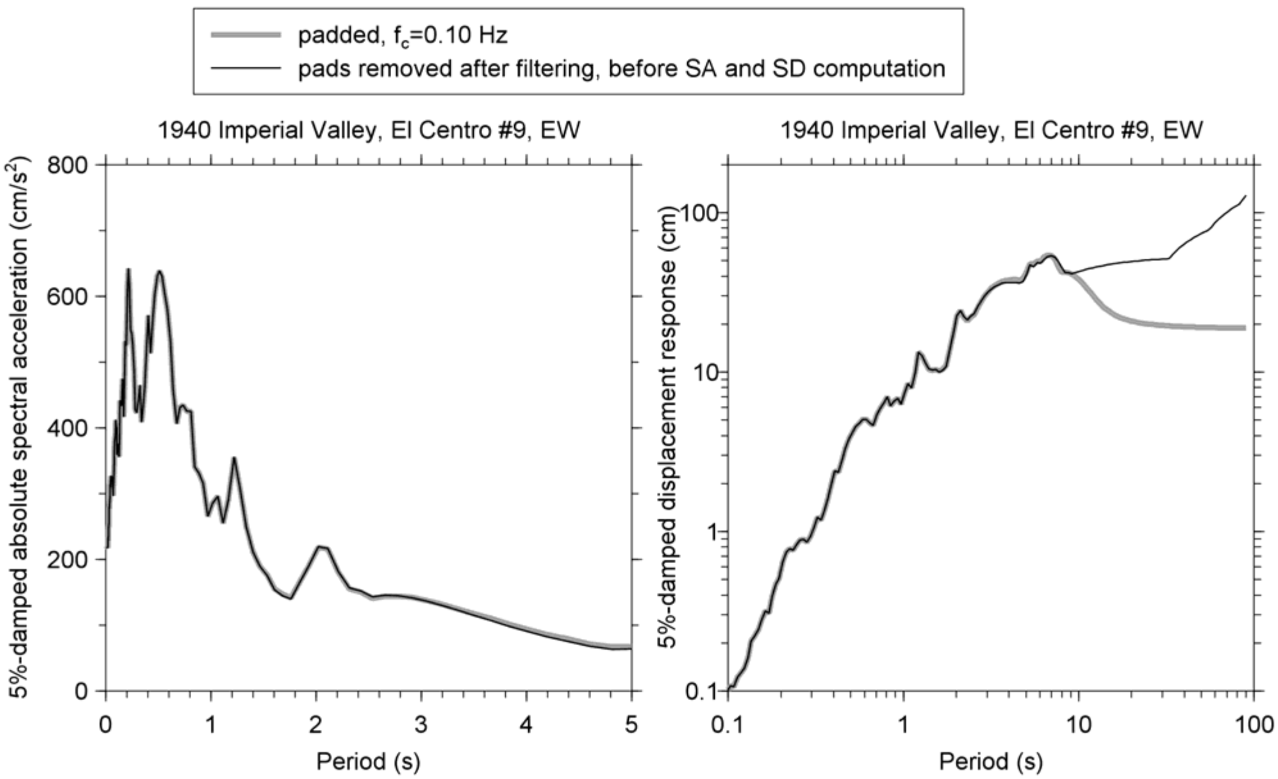

Figure 2. **Absolute acceleration response (SA) and spectral displacement (SD) computed for the El Centro station 9 recording of the 1940 Imperial Valley earthquake, from the filtered acceleration before and after removal of the zero padded portion. Note that SA and SD have been plotted using linear and logarithmic axes, respectively.**

FILTERING BY RECORD VERSUS FILTERING BY CHANNEL

Currently, records are released by agencies like the USGS and CGS with all channels filtered with the same filter corner. In many cases, it is also beneficial for the records to be released with, for example, all horizontals filtered the same or every channel filtered separately. If included, the set of individually filtered channels should be clearly indicated as an alternate set. Clear documentation for the user is important so that the difference is understood. An alternate way to address this need may be the release of the unprocessed data so that a knowledgeable user can process the records as desired.

Most accelerograms, especially analog recordings, include three orthogonal components of motion, one in the vertical direction. An issue to be considered in record processing is whether the same filter parameters should be used for all three components or whether optimal processing should be used to obtain the maximum information possible from each of the three components. If the same processing is applied to all three components, the filter cut-off will generally be controlled by the vertical component since this will usually have a lower signal-to-noise ratio than the horizontal components, particularly in the long-period range. Therefore, unless there is a compelling reason for the vertical and horizontal components to be processed with the same filter, this practice is not recommended. Similar arguments hold for strongly polarized horizontal components of motion, as may be encountered in near-source recordings, since the stronger component could be subjected to an unnecessarily severe filter because of the lower signal-to-noise ratio of the fault parallel component.

There are applications for which it is important that the components of accelerograms, especially the horizontal components, be processed in a uniform manner. These applications include resolution of the components, for example, into fault normal and fault parallel components, or to find the absolute maximum horizontal amplitude. Another example is when there are accelerograms obtained at ground level and from upper stories of buildings or from the superstructure of bridges, which will be used to compare the seismic response of the structure to predictions from modeling. In all these applications, it is particularly important to retain the phase characteristics of the motion and not to introduce any offsets in the time scale of one component with respect to another. For such applications it is vital that acausal filters be employed (unless baseline corrections are sufficient to remove long-period noise), using the same pad lengths for both components, which will therefore be determined by the filter parameters that result in the longer pads.

RELEASE OF UNPROCESSED DATA

The ability of investigators to work with unprocessed data is critical for research and progress in understanding noise characteristics, data offsets, and other issues. COSMOS member agencies are encouraged to release unprocessed (Vol. 1) data for research and, upon special request, to provide raw data as well. Organizations in a position to process data for open release are requested not to process, for release, data already released by the source network because of the potential confusion multiple releases of processed records would cause. It is incumbent upon anyone releasing reprocessed data to be very clear what the differences are relative to the original release.

A distinction may be needed between unprocessed and raw data, since the latter may be affected by 'non-standard' errors, which should be removed at the source, if possible, rather than being partially removed, or even concealed, by the application of standard processing procedures such as filters.

The noise encountered in digitized records from analog instruments is understood to arise from the characteristics of the instrument and the digitizer, and apart from the dependence of the noise on frequency it generally manifests throughout the digitized record. In many records, however, errors are sometimes found that do not correspond to the usual sources of noise (e.g., Douglas [9]). Although many of these non-standard errors will be removed–or concealed–by the application of standard processing procedures, it is preferable to identify them and, to the extent possible, remove them prior to undertaking routine processing.

An example of non-standard error is shown in Figure 3: spurious 'spikes' in the digitized record can be identified at about 10.8, 16 and 26 sec. In this particular case, the spurious nature of these spikes was confirmed by comparison with a reproduction of the original analog record; the origin of the spikes has not been ascertained, although a possible cause in this instance was the misplacement of the decimal point in transcribing the digitized values [10].

Once the spikes have been identified as erroneous, they should be removed from the digitized record; one way to achieve this is replace the acceleration ordinate of the spike with the mean of the accelerations of the data points either side. The spectra in Figure 4 were obtained with the record shown in Figure 3 before and after the spikes were removed; the spikes clearly constituted a serious noise contamination at short periods, note that their elimination appears to have led to slight modifications in the spectrum at long periods (spikes are broadband and have energy content at long as well as short periods). Of course, if the misplacement of decimal points is identified as the cause of the errors, then an exact correction could be made.

A problem encountered with some digitized analogue records is shifts in the baseline, which are presumed to be the result of the record being digitized in sections and these then not being correctly spliced together (Figure 5). The recommended procedure for dealing with such baseline offsets is the same as that used for transducer offsets in digital recordings, discussed under 'Sensor Offsets'.

USABLE DATA BANDWIDTH

The usable data bandwidth should be documented and distributed with processed data, in a manner clear to the data user. Recommendations against use of the data outside of this bandwidth should be included with the data file, and in an expanded form in documents on the agency's (or another) website. Response spectral

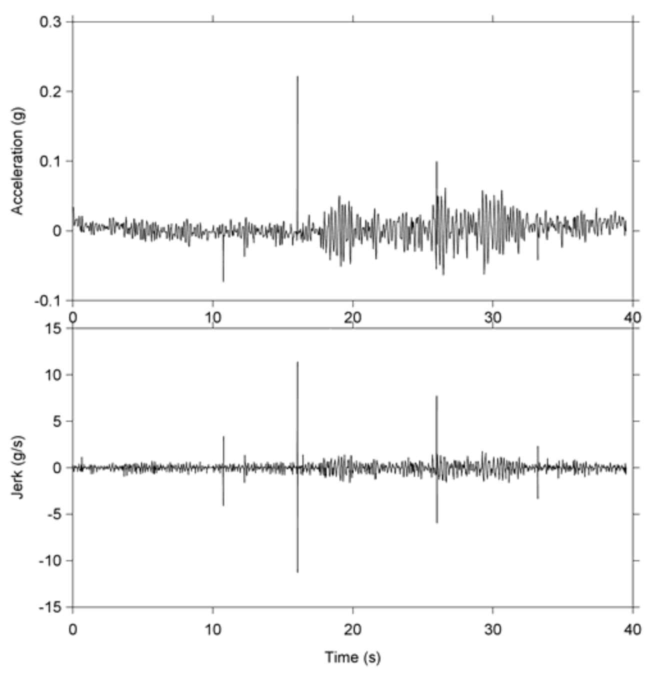

Figure 3. Horizontal component of the Bajestan recordings of the 1978 Tabas earthquake in Iran; spurious spikes are obvious in the acceleration record at 10.8 and 16 sec. The derivative of the acceleration trace (to produce the quantity called "jerk") will convert a spike into a double sided pulse, making it easier to identify spikes. By doing this (bottom panel), spikes at 12.3, 26 and 33.2 sec are also identified.

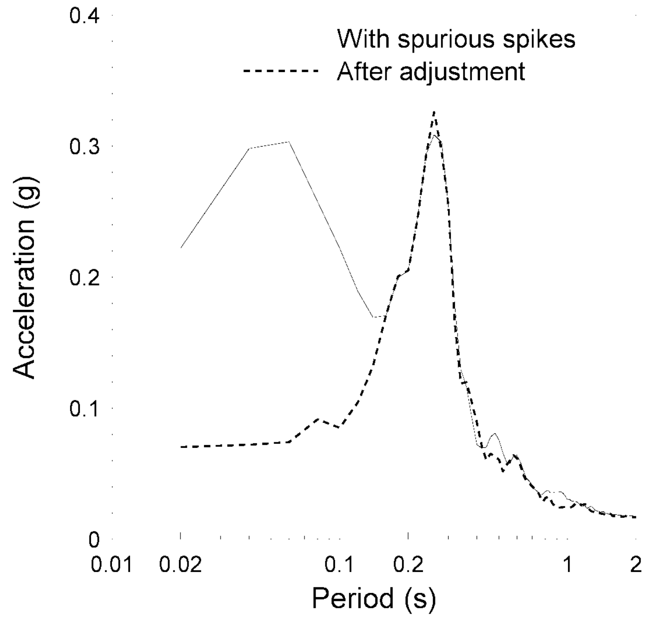

Figure 4. Acceleration response spectra (5% damped) from the accelerogram in Figure 2 before and after removal of the spikes.

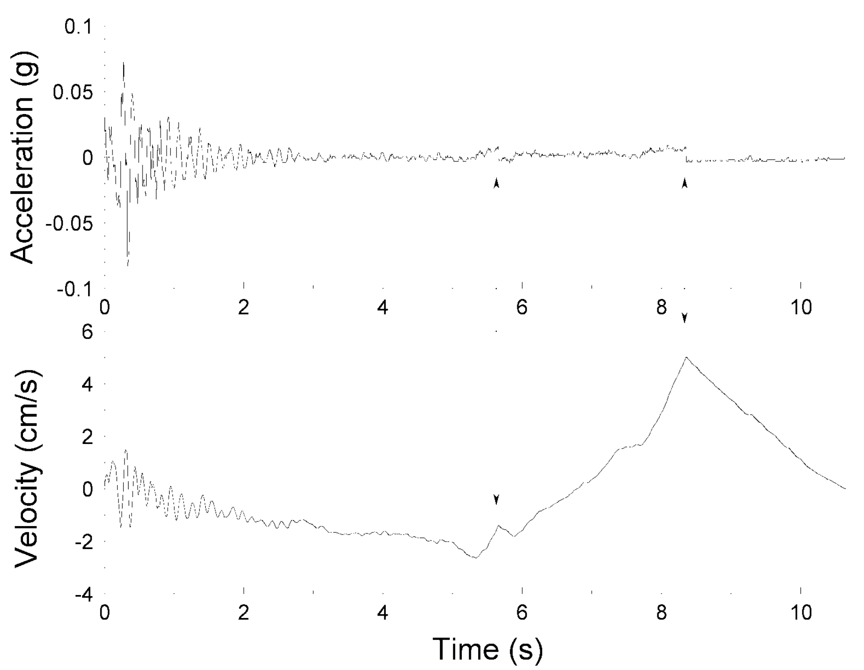

Figure 5. NS component of the 21 May 1979 Italian earthquake (12:36:41 UTC) recorded at Nocera Umbra, showing shifts in the baseline at 5.6 and 8.3 sec.

values should only be provided within the Usable Data Bandwidth defined by the processing group. This limitation should be documented to the users.

The highest frequencies at which the data can be used are generally controlled by the type of instrument and the sampling rate, as discussed under sections 'High Frequencies' and 'Instrument Correction'. A key issue is the shortest frequency, or maximum period, at which the data can be considered reliable. The amplitudes of long-period response spectral ordinates are highly sensitive to the parameters of low-cut filters, and this is most clearly visible when looking at the spectra of relative displacement. Figure 6 shows that care must be taken in deciding the range of periods for which the spectral ordinates can be reliably used, which depends on both the filter frequency and the order of the filter. For a low-order filter applied at 20 sec, the spectral ordinates should probably not be used much beyond 10 sec. The studies by Abrahamson and Silva [11] and Spudich et al. [12] to derive predictive equations for response spectral ordinates only used each record for periods up to 0.7 times the cut-off period. Bommer and Elnashai [13], in deriving predictions for displacement spectral ordinates, used each record up to 0.1 sec less than its cut-off period, which will have inevitably resulted in underestimation of the spectral displacements at longer periods. Berge-Thierry et al. [14] derived their equations from a dataset dominated (84% of the records) by records from the European Strong-Motion Database [15], which were filtered at 4 sec.

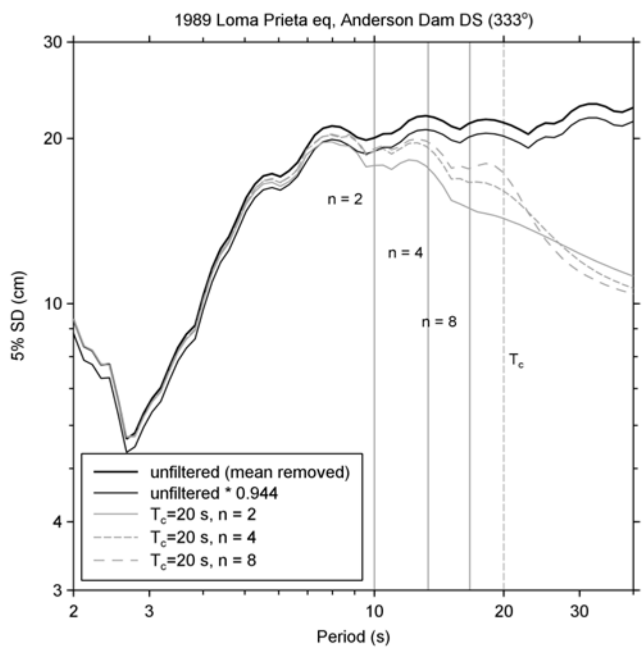

Figure 6. Response spectra with and without acausal, time-domain (2-pass) filtering. The unfiltered spectrum is shown in two versions: as is (thick line) and multiplied by 0.944 to better compare the filtered response with expectations based on the filter frequency-response analysis (thin line). The filtering is for a series of filter orders and a single value of corner frequency. The dashed vertical line indicates the filter corner. The solid vertical lines denote periods for which the filter response is down by about -1/2db (a factor of 0.94) for the various filters, as indicated by the values of filter order *n*.

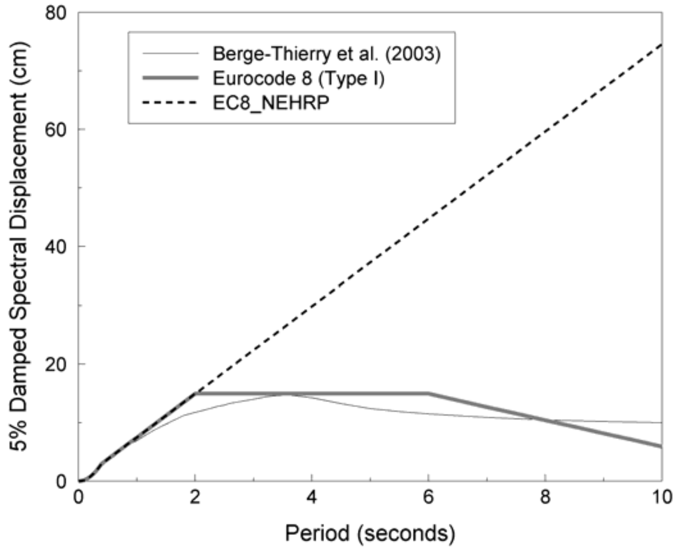

Figure 7. Displacement response spectra for rock sites due to a magnitude 7 earthquake at a hypocentral distance of 15 km obtained from the equations of Berge-Thierry et al. [14] and from Eurocode 8 [15]. The dashed line shows the form of the EC8 spectrum if the same corner.

The spectral ordinates predicted by the equations of Berge-Thierry et al. [14] at periods higher than 3.0 sec have little physical meaning and the apparent peak in the spectrum close to 4 sec is more likely to be a result of the filtering of the records than a genuine feature of the ground motion. This also casts significant doubts on the Eurocode 8 [16] spectrum, with which the Berge-Thierry et al. [14] predictions are compared in Figure 7. For most analog recordings, it is unlikely that reliable spectral ordinates can be obtained for periods much beyond 3 or 4 sec, hence the derivation of reliable long-period displacement spectra will need to be based on seismological modeling and the use of high-quality digital recordings. The NEHRP 2003 guidelines predict long-period spectral ordinates that have been restrained by either seismological criteria or digital accelerograms; digital recordings from the Denali earthquake have been shown to match very well with the 2003 NEHRP spectrum [17]. If it is assumed that the NEHRP corner periods are more applicable than the current Eurocode 8 value of just 2 seconds, the implications are that long-period spectral displacements in Eurocode 8 are severely underestimated (Figure 7).

ACAUSAL FILTERS

In general, acausal filters should be used unless there are special factors involved. This has been found to be particularly important if the data will be used to generate inelastic response spectra. Any usage of causal filters should be clearly documented in the information and comments accompanying the data. If causal filters are used (e.g., in real-time applications), it is important that the same filter corner be used for all components.

The purpose of a low-cut filter is to remove that part of the signal that is judged to be heavily contaminated by long-period noise. The key issue is selecting the period beyond which the signal-to-noise ratio is unacceptably low (see ‘Selecting Long-Period Filter Period’). Applying a filter that abruptly cuts out all motion at periods above the desired cut-off can lead to severe distortion in the waveform, and therefore a transition–sometimes referred to as a ramp or a roll-off–is needed between the pass-band, where the filter function equals unity, and the period beyond which the filter function is equal to zero. Figure 8 shows the form of a low-cut Butterworth filter, defined by a filter frequency and an order: the higher the order of the filter, the more rapid the roll-off (but with increased filter-response oscillations for the higher order filters).

Users are faced with a wide range of filters to choose from, including Ormsby, elliptical, Butterworth, Chebychev and Bessel. The choice of filter type is relatively unimportant, but the way in which the filter is applied to the accelerogram has been shown to be very important. The fundamental choice is between causal and acausal filters, the distinguishing feature of the latter being that they do not produce any phase distortion in the signal, whereas causal filters do result in phase shifts in the record. The zero phase shift is achieved in the time domain by passing the transform of the filter along the record from start to finish and then reversing the order and passing the filter from the end of the record to the beginning.

The reason that the filters are described as acausal is that to achieve the zero phase shift they need to start to act prior to the beginning of the record, which can be accomplished by adding lines of data points of zero amplitude, known as pads, before the start of the record and after the end of the record. The length of the pads depends on the filter frequency and the filter order (Figure 9). The required length of the filter pads will often exceed the usual lengths of pre- and post-event memory on digital recordings, hence it is not sufficient to rely on the memory to act as the pads.

The application of causal and acausal filters, even with very similar filter parameters (the transfer functions will not be identical if time-domain filtering is used, since the causal filter will have a value of $1/\sqrt{2}$ at the filter corner frequency, f_c, whereas the acausal filter will have a value of 0.5, regardless of the filter order),

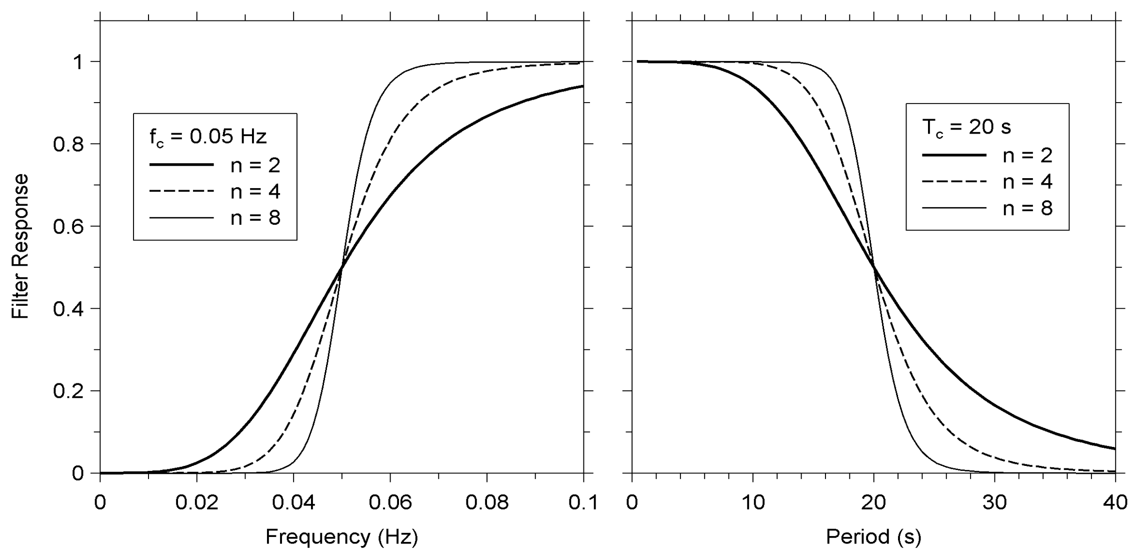

Figure 8. Illustration of a low-cut Butterworth filter as a function of frequency and period. The filter frequency is 0.05 Hz, which means that periods above 20 sec are at least partially removed. The different curves are for different orders of filter: the higher the order, the more abrupt the cut-off. For the lower order filters, information will be removed from periods as low as 10 sec.

have been shown to produce very different results in terms of the integrated displacements (Figure 10) and the elastic spectral response ordinates (Figure 11). The surprising feature of Figure 11 is the influence that the low-cut period can have on the short-period spectral ordinates when causal filters are used. The influence of causal and acausal filters on both elastic and inelastic response spectra has been investigated by Boore and Akkar [18], who found that the both elastic response spectra and inelastic response spectra computed from causally-filtered accelerations can be sensitive to the choice of filter corner periods even for oscillator periods much shorter than the filter corner periods.

END EFFECTS

In routine processing, one way late-triggered records may be treated is by tapering of the records before processing. A raised cosine applied to the first and last few percent (e.g., 5) of the record length is a reasonable taper. Late-triggered records and records with permanent offset should only be tapered with care, and for these cases a more complex (or no) tapering may be appropriate. Any tapering done should be documented. In addition to tapering, another approach is to trim the record at the location of the first and last zero-crossings in the record.

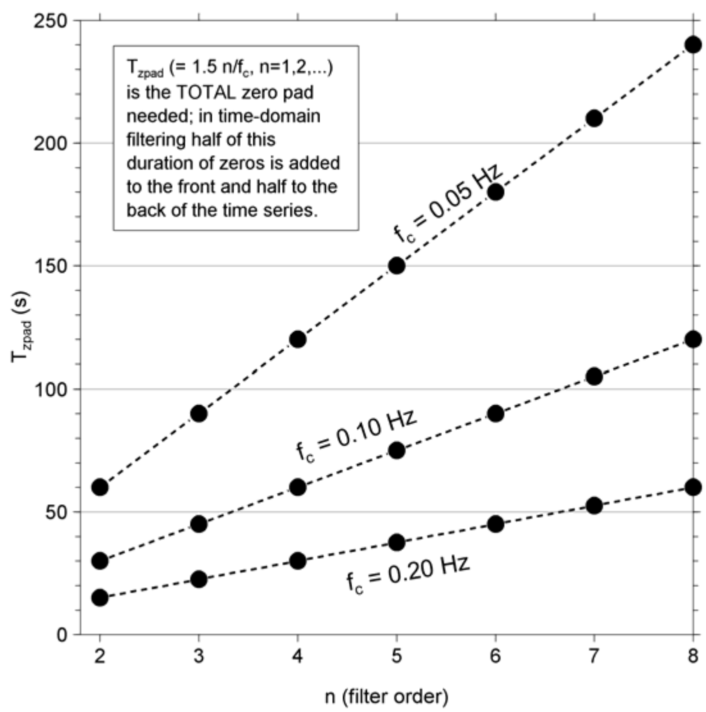

Figure 9. The total length of the time-domain zero pad recommended by Converse and Brady [7] to allow for the filter response in 2-pass (acausal), n^{th}-order Butterworth filters (these pads are needed regardless of whether the filtering is done in the time- or frequency-domain). Pre- or post-event data count as part of the required pad length. Shown are the pad lengths for three values of the filter corner frequency, as a function of filter order.

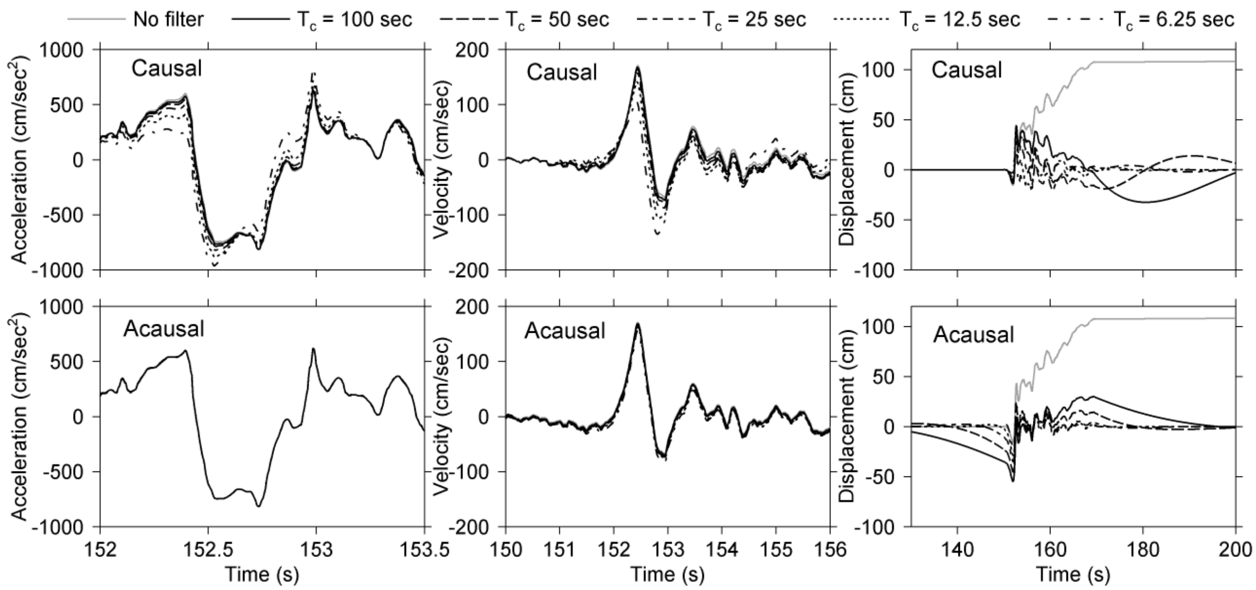

Figure 10. Accelerations, velocities, and displacements from the 228 degree component of the analog recording at Rinaldi during the 1994 Northridge earthquake for causal (*top*) and acausal (*bottom*) filtering. The time scales are different for the acceleration, velocity, and displacement time series to better display certain features.

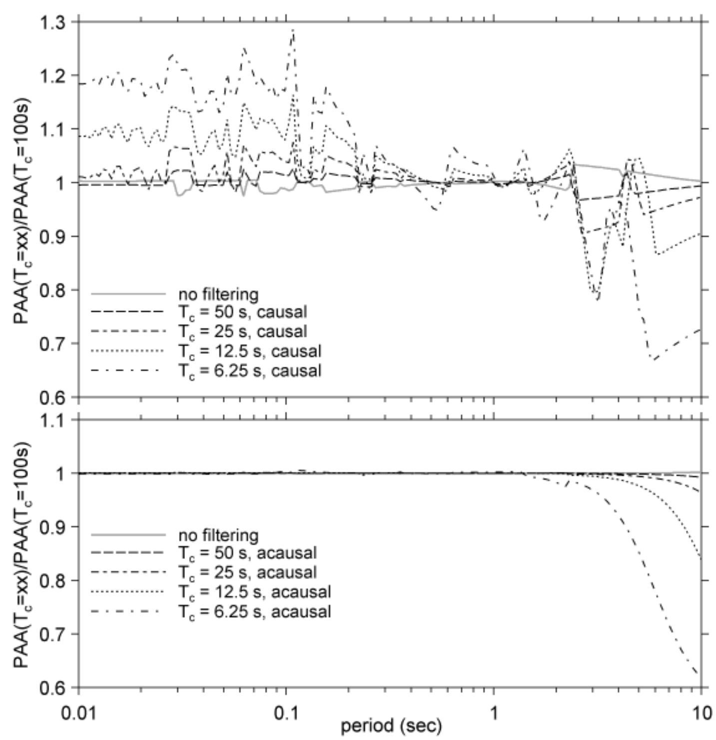

Figure 11. Ratio of 5%-damped pseudo absolute acceleration spectra (in cm/s^2) from the 228 degree component of the analog recording at Rinaldi during the 1994 Northridge earthquake for causal (*top*) and acausal (*bottom*) filtering, using the results for a filter corner of 100 sec as reference.

Processing of late-triggered records (i.e., records with little or no recorded data before the high amplitude motion) is quite uncertain, and more than normally dependent on details of the procedures used in processing. In general it is recommended that late-triggered records not be used if otherwise equivalent records are available.

When adding zero pads to accelerograms prior to filtering, a potential undesired consequence is to create abrupt jumps where the pads abut the record, which can introduce ringing in the filtered record. There are two different ways to avoid this, one being to use tapers such as a half-cosine function for the transition from the motion to the zero pad. A simpler procedure is to start the pad from the first zero crossing within the record, provided that this does not result in the loss of a significant portion of record, as can happen if the beginning or end of the acceleration time series is completely above or below zero.

TIME DOMAIN VERSUS FREQUENCY DOMAIN

In general, excluding base line corrections, careful processing done with time domain and frequency domain procedures yield comparable results.

A filter is a function that in the frequency domain has a value close to 1 in the range of frequencies that the analyst wishes to retain and close to zero in the range of frequencies that the analyst wishes to eliminate. The filter can be applied in the time domain, by convolution of its transform with the time history, or in the frequency domain by multiplying the filter function with the Fourier amplitude spectrum (FAS) of the time history, and then obtaining the filtered time history through the inverse Fourier transform. The choice between application in the time domain or the frequency domain is of no consequence and exactly the same results should be obtained in both cases if the filter response in the frequency domain is the same.

METADATA

Metadata (i.e., information about the data) should be provided with the data. To prevent confusion by users, the original metadata should be preserved in the data file; if other agencies reprocess or redistribute the data, it should indicated as original metadata. Modifications or additions to the metadata should also be clearly indicated in the metadata. A minimum set of parameters should be provided in the metadata. The set of minimum parameters remains to be defined, but indispensable amongst these is information regarding any baseline adjustments and the parameters of any applied filtering.

The most widely used–and also the most effective and least subjective–tool for reducing the long-period noise in accelerograms is the low-cut filter [19]. Figure 12 shows two accelerograms, one analog and one digital, before and after the application of filters to the acceleration time-history, and the improvement in the appearance of velocity and displacement time-histories is obvious; it should also be noted that there is little discernable difference between the filtered and unfiltered accelerations. Although the benefits of applying filters are clear, it is important to be aware of the sensitivity of the results obtained to the actual parameters selected for the filter (Figure 13). The selection of these parameters is therefore a critical issue, and the filter parameters must be recorded within the metadata. One of the many reasons for which this information is vitally important is, as explained earlier, that it effectively defines the usable bandwidth of the processed data.

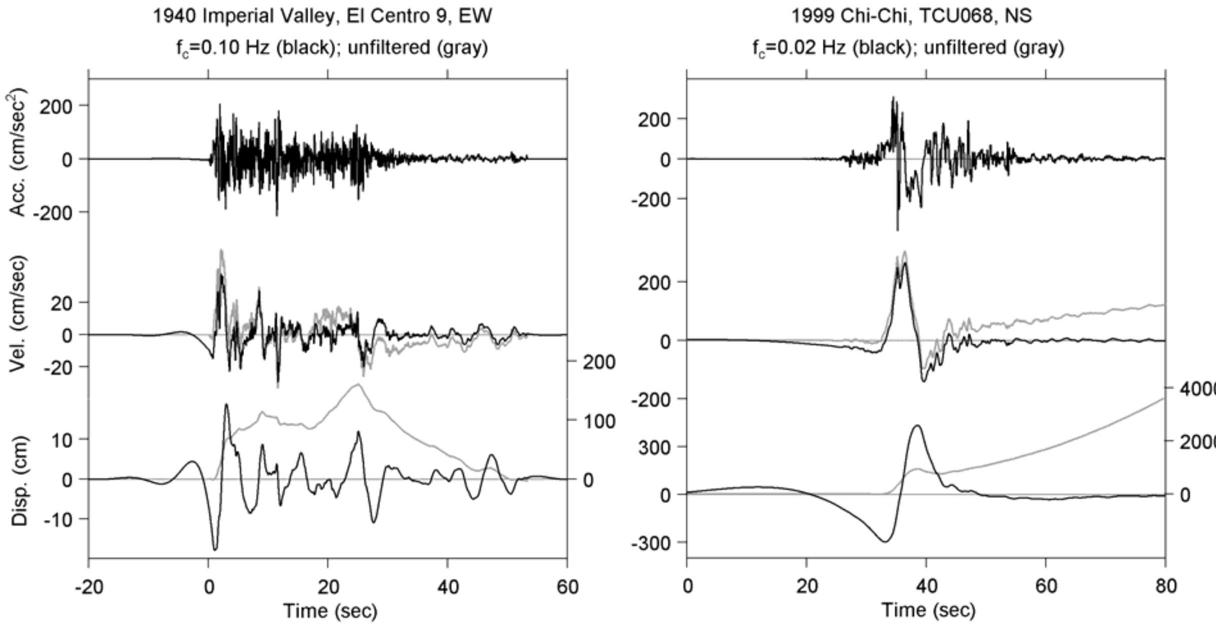

Figure 12. Acceleration, velocity and displacement from the analog and digital recordings; the only processing for the gray traces was to remove the overall mean for the analog record and the prevent mean for the digital record. The black traces show the velocities and displacements derived from acceleration time series filtered as indicated. The displacement axis labels for the unfiltered motions (gray) are given on the right side of the graphs.

HIGH FREQUENCIES

High frequencies can be important at hard rock sites, and in areas of low attenuation. Data should be provided out to as high a frequency as allowed by the signal and noise. A sampling rate as high as feasible (e.g., 200 sps or higher) is important for good definition of the strong acceleration pulses. The anti-aliasing filter of the recorder should be consistent with the sample rate.

The transducer frequency in analog instruments is limited to about 25 Hz (as opposed to at least 50-100 Hz in digital instruments), and this results in distortions of amplitudes and phases of the components of ground motion at frequencies close to or greater than that of the transducer [20] [21] [22]. The digitization process itself can also introduce high-frequency noise as a result of the random error in the identification of the exact mid-point of the film trace [23 (Figure 14)]. The degree to which either or both of these effects matter depend both on the frequency content of the ground motion and on the engineering application.

The left-hand plot in Figure 15 shows an example of the Fourier spectra of high-frequency ground motion obtained at a very hard rock site in Canada at a distance of 4 km from the source of a small magnitude earthquake. Softer sites, even those classified as ‘rock’ such as class B in the 2003 NEHRP guidelines [24], will tend to filter out such high-frequency motion. Very high-frequency motions will also tend to attenuate rapidly with distance and hence will not be observed at stations even a few tens of kilometers from the fault rupture. The plot in Figure 15 also shows the typical transducer response for the instrument (SMA-1) on which the record was obtained, and the effect of applying a correction for the instrument characteris-

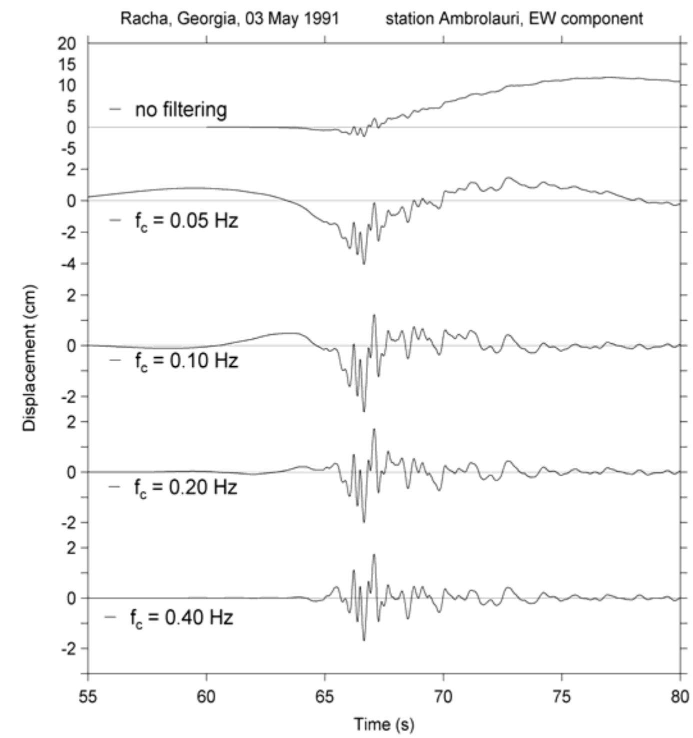

Figure 13. Displacement time-histories for a series of filters with different parameters.

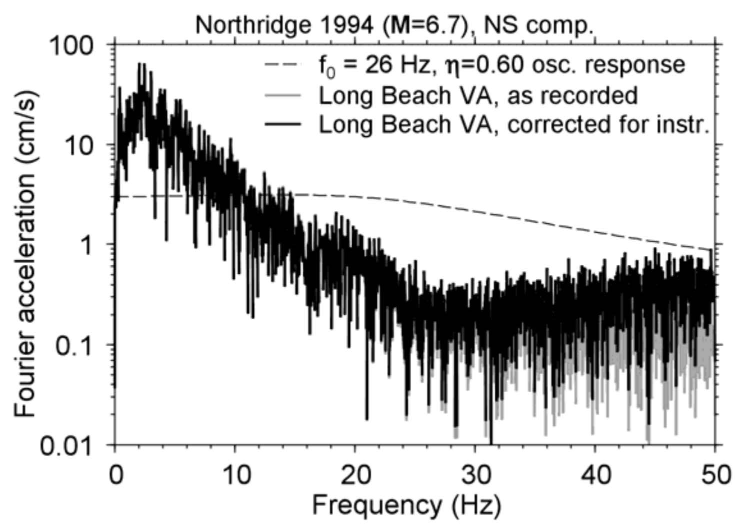

Figure 14. Fourier acceleration spectrum of an analog recording at a site underlain by thick sediments. Natural processes along the propagation path have removed energy at frequencies much below those affected by the instrument response (see dashed line; the instrument response has been shifted vertically so as not to be obscured by the data), leading to the decreasing spectral amplitudes with increasing frequency up to about 26 Hz (coincidentally the same as the instrument frequency),at which point noise produces an increase in spectral amplitudes. Instrument correction only exacerbates the contamination of the signal by high-frequency noise.

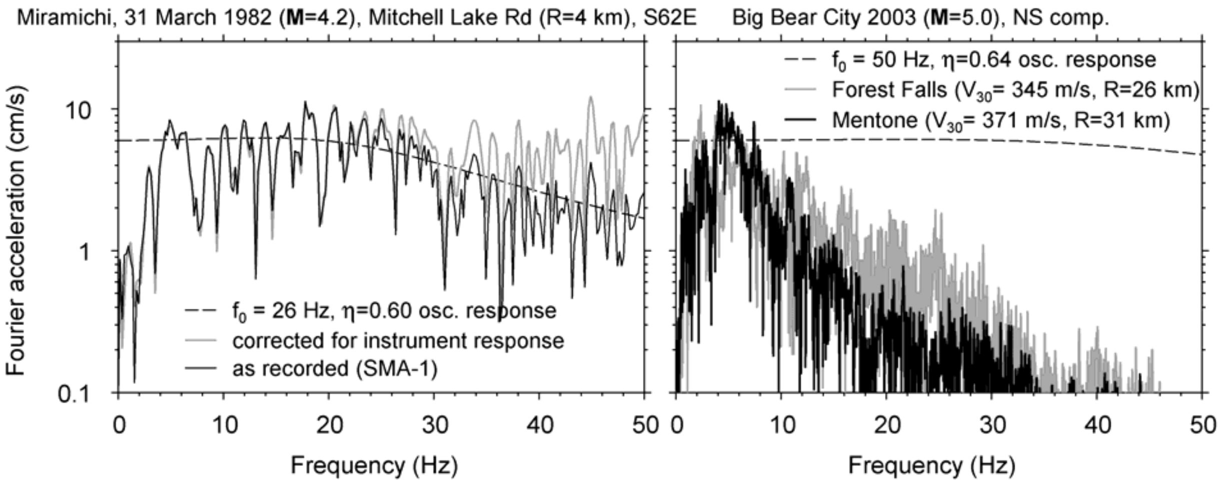

Figure 15. Fourier acceleration spectra of earthquakes recorded in eastern and western North America (left and right graphs, respectively). The eastern North America recording has much higher frequency content than that from western North America, even without instrument correction. The record from Miramichi was recorded on an analog instrument, whereas those from the Big Bear City earthquake were recorded on digital instruments (the response curves of the instruments are shown by the dashed lines and have been shifted vertically so as not to be obscured by the data).

tics, which is to increase slightly the amplitudes at frequencies greater than 30 Hz. The relevance of such motions, at periods of less than 0.03 sec, will only be relevant to particular engineering problems, such as the response of plant machinery and non-structural components. The right-hand plots in Figure 15 show the Fourier spectra of more typical ground motions obtained at soil sites during a moderate magnitude earthquake in California. These records were obtained on digital instruments and are lacking in very high frequency motion mainly because of the attenuating effect of the surface geology at these sites compared to the very hard site in Canada. The plot also shows the transducer response for these digital instruments, which is almost flat to beyond 40 Hz.

INSTRUMENT CORRECTION

Complete information about the instrument response and any instrument correction performed should be documented with the data. Early approaches to instrument corrections were based on finite difference schemes using second-order centered differences as an approximation to the derivatives, but it has been found that these are only effective if the record has been digitized at a high sampling rate [2] [25]. Second-order difference techniques are effective for frequencies up to about one-eighth of the sampling frequency. Techniques more widely used in current practice, such as that employed for the corrections shown in Figure 14 and the left-hand plot of Figure 15, generally perform the correction by using either higher-order approximations to the derivatives or using frequency-domain corrections [2] [7]. The key issue, however, is less about which particular procedure to apply but rather whether an instrument correction should be applied at all. For digital recordings, instrument corrections should not be necessary. For analog recordings, if the engineering application is concerned with motions at frequencies above 20 Hz and the site characteristics are sufficiently stiff for appreciable amplitudes at such frequencies to be expected, a correction should be considered. It should be noted, however, that the instrument corrections essentially amplify the high-frequency motions; if the digitization process has introduced high-frequency noise into the record, then the instrument correction will amplify this noise. Unless there are compelling reasons for applying a correction for the instrument characteristics, we recommend that no attempt should be made to do so. The one exception to this may be the very earliest recordings obtained in the United Stateswith accelerographs that had natural frequencies of the order of 10 Hz.

SENSOR OFFSETS

Sensor offsets can be a significant issue with modern data. The presence of offsets should be checked as a part of determining whether routine processing can be applied (e.g., by removing a suitable reference level(s) and checking the velocity for trends, or equivalently checking for different DC acceleration levels at the start and end of a record). Offsets can be estimated by several techniques; the most successful at this time requires a case-by-case approach involving inspection of intermediate time series and/or spectra.

Figure 5 illustrated a problem sometimes encountered in digitized versions of analog recordings due to shifts in the baseline (see 'Release of Unprocessed Data'). A very similar problem is frequently encountered in accelerograms from digital instruments, although the cause in those cases is often related to the actual instrument operation [26] [27] [28] [29] or even the process of analog-to-digital [29].

Figure 16 illustrates the application of a piece-wise sequential fitting of baselines to the velocity trace from a digital recording in which there are clearly identifiable offsets in the baseline. A similar procedure could be applied directly to the acceleration time-history to correct for the type of baseline shifts shown in Figure 5. The procedure applied in Figure 16 is to identify (by blowing up the image) sections of the velocity that appear to have a straight baseline, and then fitting a straight line to this interval. This line in effect is then subtracted from the velocity trace, but in practice it is necessary to apply the adjustment to the accelerations. The adjustment to the acceleration is a simple shift equal to the gradient (i.e., the derivative) of the baseline on the velocity; this shift is applied at a time t_{v0}, which is the time at which the line fit to the velocity crosses the zero axis. The adjusted velocity trace is then inspected to identify the next straight line segment, which is fit in the same way. In the particular case illustrated in Figure 16, a total of four line segments were required to remove the most severe distortions of the baseline visible in uppermost plot, although the baseline instabilities are not entirely removed, as evident in the residual long-period trends.

SELECTING LONG-PERIOD FILTER PERIOD

In the absence of offsets (or after correction for them) the long-period filter corner selection should incorporate analysis of signal and noise. Using a ratio of recorded signal-to-noise of not less than 2 is recommended. This selected period should be reviewed in the time domain to verify that clearly unphysical velocity and displacement time series are not produced (when possible, considering similarity of displacements obtained for nearby stations is a recommended technique). Peak displacement is strongly dependent on the long-period filter corner. True permanent displacement may, in general, not be obtainable from triaxial strong-motion records alone.

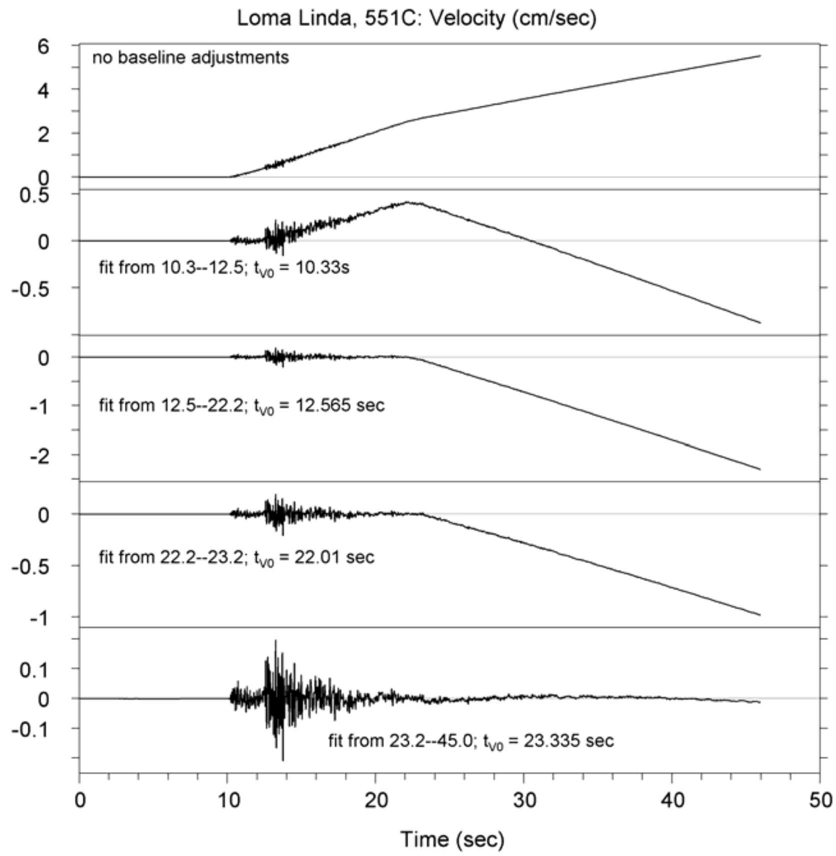

Figure 16. Sequential baseline adjustments applied to the velocity time-history obtained from integration of a digital accelerogram with shifts in the baseline. Note the change in the ordinate scales of the plots.

Due to uncertainty in obtaining permanent displacement from accelerometers, networks are encouraged to include direct measurement of displacement (e.g., selective co-location of differential GPS instruments) in strong-motion networks.

The most important issue in processing strong-motion accelerograms is the choice of the long-period cut-off, or rather the longest response period for which the data are judged to be reliable in terms of signal-to-noise ratio. A number of broad criteria can be employed by the analyst to infer the period beyond which it is desirable to apply the filter cut-off, including:

- Comparison of the FAS of the record with that of a model of the noise, obtained from the pre-event memory for digital records, the fixed trace from analog records or from studies of the instrument and digitizing apparatus. A point of clarification is appropriate here regarding signal-to-noise ratios: the comparison of the record FAS with the FAS of the noise indicates the ratio of signal-plus-noise to noise, hence if the desired target is a signal-to-noise ratio of 2, the ratio of the record FAS to that of the noise model should be 3.

- Judgment of where the long-period portion of the record FAS deviates from the tendency to decay in proportion to the reciprocal of the frequency squared. Whether one assumes the single corner-frequency model of Brune [30] [31] or the more complex models with two corner frequencies [32] [33] [34] [35], seismological theory dictates that at low frequencies, the FAS of acceleration decays according to f^2 (by virtue of the fact that the long-period displacement time series radiated from earthquakes will be pulse-like, ignoring residual displacements, and the FAS of the displacement pulse will therefore be finite at zero frequency).
- Visual inspection of the velocity and displacement time-histories obtained by double integration of the filtered acceleration, and judgment of whether or not these quantities appear to be unphysical. An adjective often used to justify the filter parameters on the appearance of the resulting velocities and displacement is 'reasonable', but this is poorly defined and what is reasonable to one observer may not be so for another.

The optimum approach is to make use of all three criteria simultaneously. The first two options are illustrated in Figure 17 for the selection of filter parameters for a component of the Anderson Dam (analog) recording of the 1989 Loma Prieta earthquake. The FAS of the record is compared with the model for the digitization noise proposed by Lee and Trifunac [6]; other studies of typical noise resulting from different digitization processes are presented by Lee and Trifunac [4], Trifunac et al. [21], Hudson [22], Shakal and Ragsdale [36], Trifunac and Todorovska [37], and Skarlatoudis et al. [38]. Also shown is the gradient of the f^2 line, superimposed as a best fit (by eye) on the section of the FAS where the decay at low frequencies commences. Also shown in the graph are the FAS of the record after applying filters with three different low-frequency cut-offs. Note that these decay more rapidly than indicated by the f^2 model, which is the expected result of effectively trying to remove all of the record–both signal and noise–at periods greater than the cut-off. Designing a filter with a gradual roll-off that will produce an FAS that approximates to the f^2 model is not advisable since the agreement with the theoretical seismological model would not mean that the real earthquake signal has been recovered, but only that an unknown mixture of signal and noise has been manipulated to produce the appearance of a genuine seismic motion.

Figure 18 shows the acceleration, velocity and displacement time-series obtained by applying the three low-cut filters in Figure 17. The largest discernable differences are in the displacement traces, with the peak amplitude varying by a factor of about three. However, none of the three displacement time-series could be judged to be clearly unphysical, although there do appear to be some unusual long-period fluctuations in the record filtered at 20 sec. This suggests that whilst the appearance of the velocities and displacements may serve to reject some filter options, it is unlikely to indicate an unambiguous choice of optimal filter parameters.

An important issue is whether records from different stations should be processed without regard to the processing of data from nearby stations that have recorded the same earthquake. Figure 19 shows the location of strong-motion accelerographs that recorded the 2002 Denali fault earthquake in Anchorage, all at distances from the fault rupture of more than 290 km. The map shows that the stations were located on sites that fall into three different classes according to the NEHRP scheme.

Figure 20 shows displacement traces of all three components from two of the stations, located on different site classes. Although the two records display different proportions of high-frequency radiation by virtue of the different stiffness of the near-surface geology at the two locations, there is a remarkable degree of coherence in the long-period part of the motion. This coherence at long periods is frequently observed and where there are large numbers of records from a given earthquake, the coherence can be used as an additional criterion to assess whether appropriate filter parameters have been applied [40] [41]. An example of such spatial coherence is given in Figure 21. An exception to this will be the case of near-source recordings affected by rupture directivity effects (e.g., [42], unless the stations are very close together.

A final point concerns an additional criterion, which although not a basis for selecting the filter parameters may serve to judge whether the chosen low-cut filter is appropriate or indeed acceptable. The theoretical FAS of earthquake ground motion, if following a single corner-frequency model, begins to decay in amplitude at frequencies lower than the corner frequency f_0. The corner frequency is essentially proportional to the inverse of the rupture duration which, since rupture propagation velocities are usually between 2 and 3 km/sec, is related to the length of the fault rupture and hence the magnitude (or moment) of the earthquake. If the signal-to-noise ratio demands that a high filter cut-off is set at a frequency higher than f_0, it means that an integral part of the signal is being removed and the filtered data is of little physical significance and hence should used with caution.

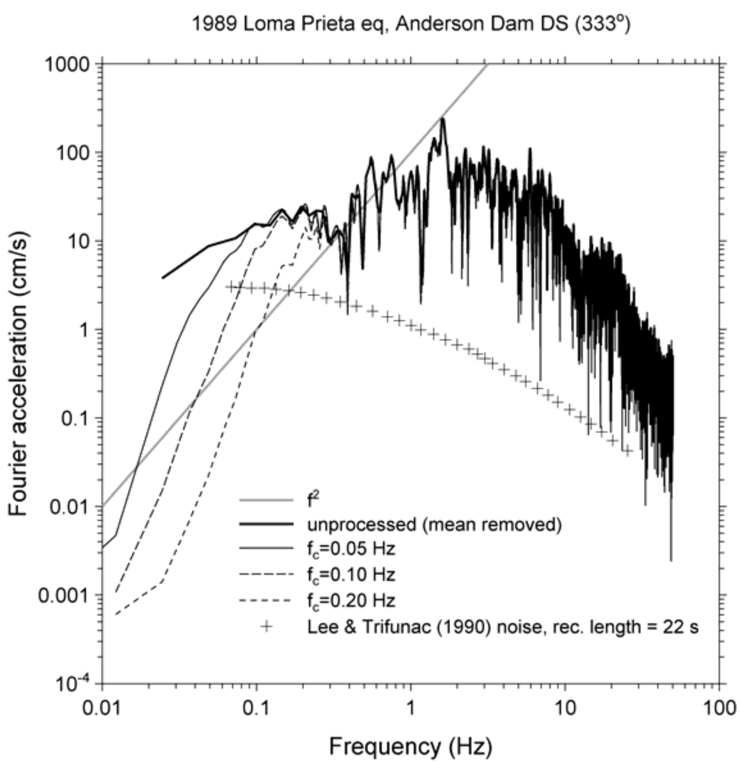

Figure 17. Fourier acceleration spectrum of a digitized version of an analog recording for three values of f_c. Also shown is the theoretical low-frequency slope for a single-corner source model, and representative noise curves from Lee and Trifunac [6], from which a signal-to-noise ratio of 3 would suggest that the filter corner should be near 0.06 Hz.

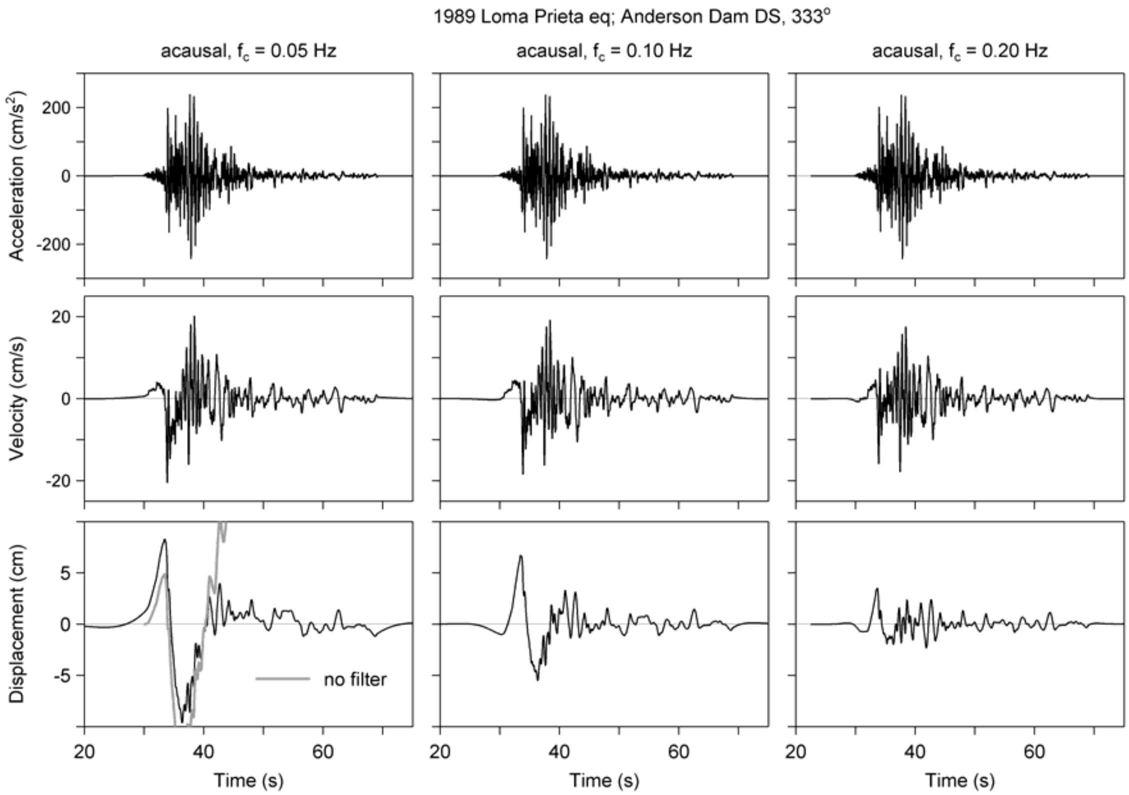

Figure 18. Acceleration, velocity, and displacement using three values of f_c. The displacement from the unfiltered acceleration is shown in gray.

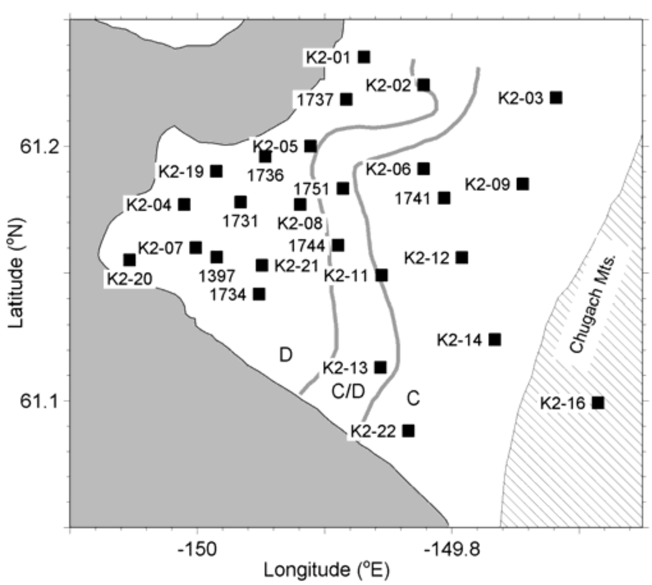

Figure 19. Location of stations and NEHRP site classes (site classes and base map from Figure 12 in [39]). The C/D class is intermediate between NEHRP classes C and D, and is defined here by the average 30 m shear wave velocity being between 320 and 410 m/s [39].

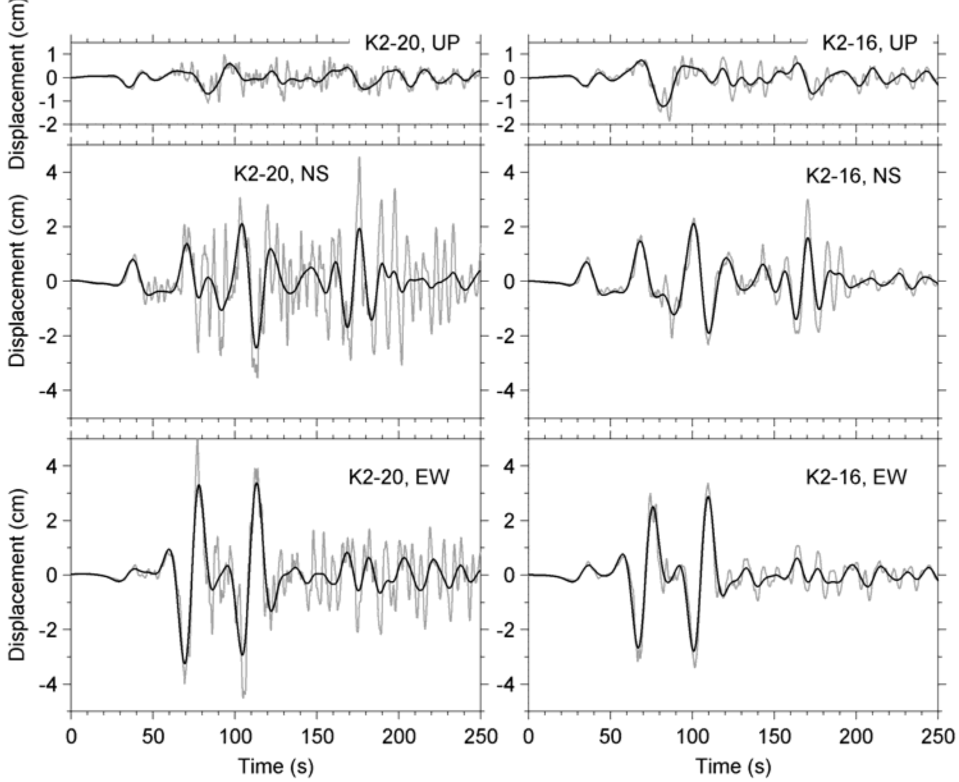

Figure 20. Displacements at stations K2-16 and K2-20 (see Figure 19), showing the strong coherence at low frequencies. Station K2-20 is on lower velocity materials and has more high frequency motion than does station K2-16. Gray curves have been low-cut filtered at 0.02 Hz; black curves have been low-cut filtered at 0.02 Hz and high-cut filtered at 0.08 Hz.

To derive predictive equations for peak ground-motion parameters in Europe, Tromans and Bommer [43] used a databank of mainly analog recordings, selecting the filter parameters mainly on the basis of inspection of the velocity and displacement time-histories obtained from the filtered accelerations. Subsequent inspection of the filter frequencies revealed that many of these were above the theoretical corner frequencies, especially for small-to-moderate magnitude earthquakes, which casts doubt on the reliability of the results for peak ground velocity (PGV) and peak ground displacement (PGD). The close agreement of these predictive equations with those of Margaris et al. [44] suggests that the latter were also based on data for which excessively severe filters may have been applied. This is not to say, however, that either study is in itself erroneous, but rather that analog data may be of limited usefulness other than to derive predictions of spectral acceleration ordinates at periods shorter than about 2 or 3 sec.

A point worthy of mention is the alternative procedure of using baseline fitting techniques in place of long-period filters. Procedures have been proposed by Iwan et al. [26], Grazier [45], Boore [46], and Zhu [47]. One of the possible advantages of baseline fitting techniques just discussed is that the displacement trace can obtain a constant level at the end of the motion and can have the appearance of the residual displacement expected in the vicinity of faults (Figure 22). This character of the displacement record cannot be achieved using low-cut filters.

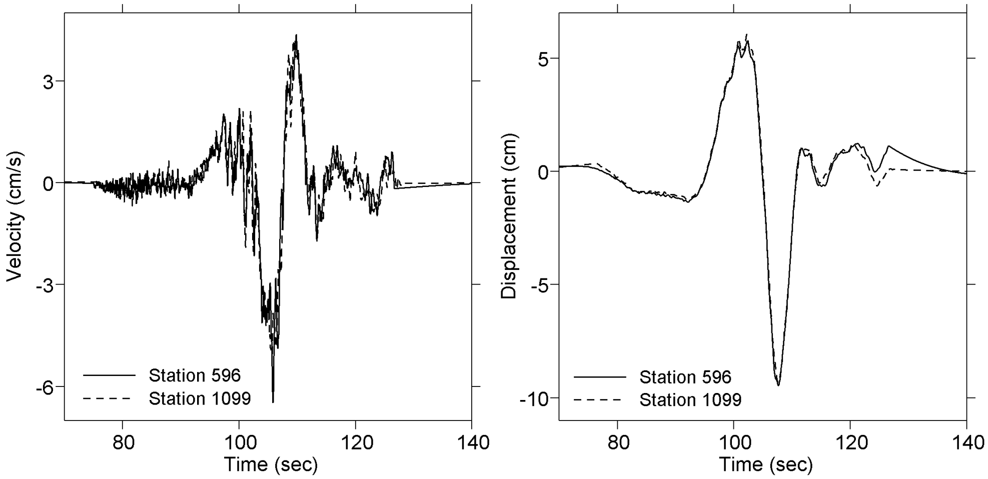

Figure 21. Comparison of the processed velocity and displacement traces from the N-S components of two stations located about 1.6 km apart and about 160 km west of the M_w 7.2 Hector Mine earthquake in 1999. Note the remarkable similarity between the signals at these two stations, particularly at long periods. Comparisons such as this are used to confirm that proper filter corners were selected to process the records.

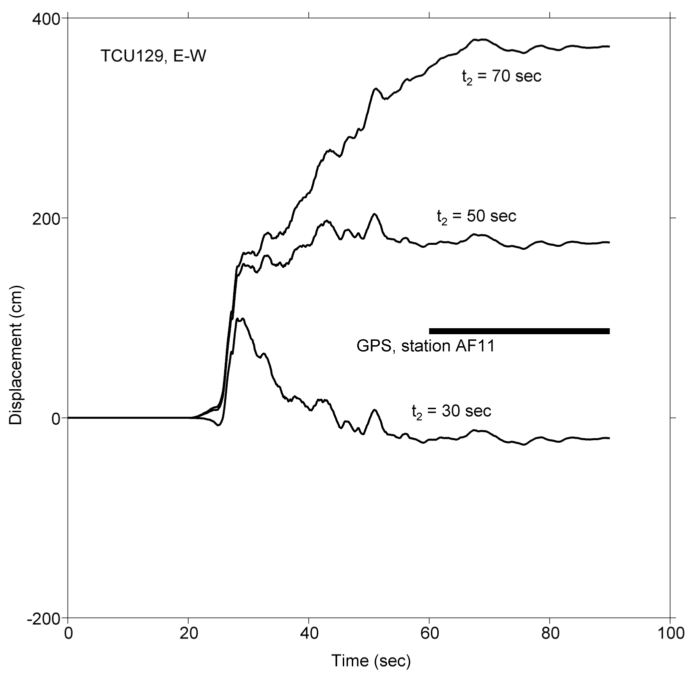

Figure 22. Displacements obtained by double integration of the east-west component of acceleration recorded at TCU129 from the 1999 Chi-Chi, Taiwan, earthquake and modified using a variety of baseline corrections. The GPS level was obtained at a station 2.3 km from TCU129, above the footwall of the fault (as is TCU129). (From [41]).

At the end of the ground shaking caused by an earthquake, the ground velocity must return to zero, and this is indeed a criterion by which to judge the efficacy of the record processing. The final displacement, however, need not be zero since the ground can undergo permanent deformation either through the plastic response of near-surface materials or through elastic deformation of the Earth due to co-seismic slip on the fault. Close to the fault rupture of large magnitude earthquakes (~ M_w 6.5 and above) this residual displacement can be on the order of tens or hundreds of centimeters. The problem presented by trying to recover the residual displacement through baseline fitting is that the resulting offset can be highly sensitive to the choice of parameters (Figure 22); furthermore, there are few data with independently-measured offsets exactly at the location of strong-motion instruments. The lack of independently-measured offsets is becoming a moot point with the installation of continuous GPS stations sampled at sufficiently high sampling rate co-located with accelerographs. A good example of this is on the island of Hokkaido in Japan, where 1 sps continuously-recording GPS instruments are collocated at a number of strong-motion sites. These instruments recorded the M_w 8.3 2003 Tokachi-Oki earthquake. The displacements from the GPS instruments agree well with those derived from accelerometers for the first half-cycle of the S-wave arrival (after which the GPS instruments failed to record the motion) [48]. Another very valuable set of co-located recordings from a strong-motion accelerograph (station PKD) and a continuous GPS recording at 1 sps was obtained during the M_w 6.5 San Simeon, California, earthquake of December 2003 [49] and the September 2004 Parkfield, California, earthquake.

Some researchers have concluded that it is actually impossible to recover with certainty the permanent offset of the ground from records of the translational movement alone, and that the true displacements can only be determined if the rotational components of the motion are also known [50] [51].

PROCESSED DATA FORMAT

To increase convenience for data users and simplify data exchange with other networks, processing agencies are encouraged to release their processed data in the COSMOS format (www.cosmos-eq.org), or alternatively, to provide a conversion module at their website to convert files from their format to the COSMOS format.

This recommendation needs little comment, other than to underscore the importance of being able to convert easily from one format to another. We do recommend, however, that data files be in ASCII format for maximum portability and ease-of-use. The decreased storage space provided by binary formatted files is no longer an important issue. In addition, compression algorithms can be easily used to reduce file sizes for storage purposes.

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