Real-time Monitoring of Ground Motion for Development of Early Warning System

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Abstract

We have developed a method to continuously monitor ground-motion parameters to minimize the impact of the sudden increase in the workload on a seismic network during a major earthquake. In this method, an earthquake is not treated as a special event, but is part of continuous perturbation of ground motion. The incoming continuous seismic data are processed with the use of various time-domain recursive filters to compute ground-motion velocity, acceleration, energy, Wood-Anderson seismograms, and narrow-band responses at 0.3, 1.0 and 3.0 sec which are used for computation of response spectral amplitudes. The continuous time-domain method has advantage over the traditional frequency-domain method for streamlining the operation of a seismic network, especially during a complex seismic sequence. The method has been tested in the Southern California Digital Seismic Network (e.g. TERRAscope and TriNet) for nearly 2 years, and is used for real-time magnitude and ground-motion amplitude reporting purposes. If the method is implemented in the individual datalogger at every field station, it would be possible to telemeter desired amplitude information (acceleration, velocity, displacement, Wood-Anderson, spectral responses etc.) with sufficient accuracy from a field station to the network center through a relatively slow communication line (e.g. regular digital telephone line).

Research

As modern broad-band and wide dynamic range seismic instruments have become widely available, real-time monitoring of earthquake ground motion is becoming an important function of a seismic network for earthquake hazard mitigation purposes. Relevant amplitude parameters include acceleration, velocity, displacement, energy, Wood-Anderson response, narrow-band responses at various periods to be used for computation of response spectral amplitudes. Traditionally, most seismic networks operate in "trigger" mode Even if the data are recorded continuously, computation of amplitude parameters is initiated only when a significant seismic event is detected. In this mode, the work-load on the system increases suddenly during a major earthquake, which could cause a system failure during the time when real-time data are most needed for emergency services To alleviate this problem, we developed a "continuous" monitoring method which continuously computes ground-motion parameters regardless of whether earthquakes are occurring or not; an earthquake is not treated as a special event, but is part of continuous perturbation of ground motion. This minimizes the fluctuation of work-load, and assures more reliable overall operation of the system. In practice, we replace the traditional frequency-domain analysis with application of a set of time-domain recursive filters and process data, sample by sample, as the signal comes in through telemetry. This is a simple conceptual change, but we believe that it would lead to a significant improvement in seismic network operation in the future. Switching the traditional frequency-domain method to a time-domain method may appear relatively simple and straightforward but, in practice, we found several important technical problems to solve for establishing a simple yet reliable procedure.

The purpose of this paper is to address these technical issues with the hope that a continuous method can be easily implemented, if desired, in other networks with a similar objective: reliable real-time ground-motion monitoring. Also, the method described here can be implemented in a datalogger itself. Such a datalogger can process data on site to compute desired amplitude parameters (acceleration, velocity, displacement, Wood-Anderson and spectral responses etc), and send them to a network central processing site. In this case, even a relatively slow communication line (e.g. regular digital telephone line) would be adequate, and would significantly simplify the deployment of a real-time ground-motion monitoring network.

We have tested the method on-line in the Southern California Digital Seismic Network (e.g. TERRAscope and TriNet) for nearly two years. This continuous system is currently used for on-line magnitude reporting, and for broadcasting ground-motion data (acceleration and velocity) through ShakeMap (Wald et al. 1998).

In the following, we describe the method applied to broad-band instruments and strong-motion accelerographs. The broad-band instruments used here are Streckeisen STS-1, STS-2, and Guralp CMG-40T seismometers, and the strong-motion instrument is Kinemetrics FBA-1 accelerograph. The method should be applicable to other instruments with similar characteristics In the following, the output from the broad-band instruments is assumed to be proportional to ground-motion velocity over the frequency band of our interest, and that from accelerographs is assumed to be proportional to ground-motion acceleration. The broad-band channel with a sampling interval (Dt) of 0.05 sec is called vbb channel, and that with either

Dt=0.0125 or 0.01 sec is called vsp channel. The acceleration channel with either Dt=0.0125 or 0.01 sec is called lg (low-gain) channel.

In the TriNet application, the filters need to be applied on-line to a large number of channels (3-component 100 sps (80 sps for some stations) accelerographs and 20, and 80 or 100 sps broad-band instruments) from many (about 60 now, and will be 200 in a few years) stations. Thus, we tried to use the simplest possible filters with small number of filter coefficients, while maintaining sufficient accuracy for amplitude computations. This restriction would not apply to implementation of the method in a datalogger.

Processing of vbb and vsp channels

The output from the instrument is assumed to be proportional to ground-motion velocity.

Acceleration

The acceleration a_j is computed simply by,

$$a_j = (z_j - z_{j-1}) / (g_{vbb} \Delta t) \qquad (1)$$

where z_j is the output from either vbb or vsp channel, Dt is the sampling interval and g_{vbb} is the gain factor. Since the gain factors for vbb and vsp channels are usually the same, we use the same symbol g_{vbb} for both.

Wood-Anderson Response

The Wood-Anderson response, w_j , is computed using the following difference equation, which corresponds to the differential equation for the Wood-Anderson response to velocity input,

$$(w_j - 2w_{j-1} + w_{j-2}) / \Delta t^2 + 2hw_0(w_j - w_{j-1}) / \Delta t + w_0^2 w_j = (g_{wa} / g_{vbb})(z_j - z_{j-1}) / \Delta t \qquad (2)$$

where h, w_0, and g_{wa} are the damping constant, natural angular frequency, and the gain factor of the Wood-Anderson instrument. The recursive filter corresponding to (2) is given by,

$$w_j = \frac{1}{c_2}\left[(g_{wa} / g_{vbb})\Delta t(z_j - z_{j-1}) + 2c_1 w_{j-1} - w_{j-2}\right] \qquad (3)$$

where

$$c_1 = 1 + hw_0 \Delta t \qquad (4)$$

and

$$c_2 = 1 + 2hw_0\Delta t + (w_0\Delta t)^2 \tag{5}$$

The transfer function corresponding to this filter (equation 3) is given by

$$F(w) = \Delta t\left(\frac{g_{wa}}{g_{vbb}}\right)\frac{1-e^{-iw\Delta t}}{c_2 - 2c_1 e^{-iw\Delta t} + e^{-2iw\Delta t}} \tag{6}$$

In comparison, the analytic Wood-Anderson response is given by

$$F_0(w) = \left(\frac{g_{wa}}{g_{vbb}}\right)\frac{iw}{w_0^2 - 2ihw_0 - w^2} \tag{7}$$

For the standard Wood-Anderson instrument, h=0.8, w_0=2p/0.8 sec^{-1}, g_{wa}=2800 (Richter, 1958). However, because of the use of the difference equation with a finite Dt (0.05 sec), the response calculated from (6) is not accurate. This error (difference between equations 6 and 7) decreases as Dt decreases To minimize the error, these constants are adjusted in the least-square sense (minimize $\left(|F(w)| - |F_0(w)|\right)^2$), so that the error in the overall response is less than 5 % over the frequency band of 0.05 to 6.5 Hz for vbb channel, as shown in Figure 1. This adjustment is an important element of the design of the recursive filter for the Wood-Anderson response. The adjustments for vsp channel are smaller, and the error is less than 1% over the frequency band of 0.01 to 10 Hz. The adjusted constants are given in Table 1.

Narrow-band Response for Computation of Response Spectral Amplitudes

The response spectral amplitude is determined from the maximum amplitude of a narrow-band response of a simple pendulum with the desired natural period (Hudson, 1979, Jennings, 1983). The computation of this narrow-band response can be performed in exactly the same manner as the Wood-Anderson response, using (2) and with appropriate values of h and w_0, with a gain factor of unity. The only difference is that the response is sharply peaked because of the small damping It is generally difficult to obtain a sharply peaked response with a recursive filter with a small number of coefficients.

The response spectra are normally computed at T_0(=2p/w_0)=0.3, 1 and 3 sec, with a damping constant h=0.05 and a gain factor g=1. However, the recursive filter using these constants completely fails to reproduce the peaked response. The actual values of T_0, h, and g need to be modified to correct for the errors due to the finite difference computation. These constants were determined to match the response in the least square sense, as is done for the Wood-Anderson response. The modified constants are given in Table 1. We note that the damping constant is modified from 0.05 to -0.461 for vbb channel, and to -0.0583 for vsp channel. The negative damping constant may appear somewhat strange, but as shown later, the recursive filters with a negative damping constant are stable and produce accurate responses. The responses for T_0=0.3 are shown in Figures 3 and 4 for vbb and vsp channels, respectively. Since the response is very narrow band, the large error for vbb channel at f   6Hz is of little consequence. The response for vsp channel is accurately computed with the adjusted constants For T_0=1 and 3 sec, the response can be more accurately computed.

Velocity

To remove the base-line offset and the long-term drift of the output from a very broad-band instrument, a high-pass filter, H1, is applied (Allen, 1978, Shanks, 1967). This high-pass filter is given in the form (x_j: input, y_j: output):

$$\text{H1:} \quad y_j = \frac{1}{b_0}\left[\sum_{k=0}^{2} a_k x_{j-k} + \sum_{l=1}^{2} b_l y_{j-l}\right] \tag{8}$$

where a_0=1, a_1=-1, a_2=0, b_0=2/(1+q) b_1=2q/(1+q), b_2=0. The constant q determines the high-pass band The transfer function of this filter is given by

$$H1(w) = \frac{1+q}{2}\frac{1-e^{-iw\Delta t}}{1-qe^{-iw\Delta t}} \tag{9}$$

The amplitude response is shown in Figure 5 for three values of q=0.999, 0.998, and 0.997. Figure 5 shows that if q=0.998, the response is less than 0.8 at periods longer than 116 and 23 sec for Dt=0.05 and Dt=0.01 sec, respectively.

Using this filter, the velocity, v_j , is computed by,

$$v_j = \frac{1+q}{2}\frac{z_j - z_{j-1}}{g_{vbb}} + qv_{j-1} \tag{10}$$

where z_j is the output from vbb or vsp channel.

Energy (integral of velocity squared)

The energy, e_j , is computed from velocity by,

$$e_j = (v_j^2 + v_{j-1}^2)\Delta t / 2 + e_{j-1} \tag{11}$$

Since the energy is a monotonically increasing function of time, it is computed for a predetermined time interval (e.g. 5 sec), and is reset to 0, at the end of each interval.

Displacement

The displacement, d_j , is computed from velocity, v_j , by integration and high-pass filtering with H1. The high-pass filter is applied to avoid long-term drift of the baseline Applying H1 again, we obtain,

$$d_j = \frac{1+q}{2} \frac{v_j + v_{j-1}}{2} \Delta t + q d_{j-1} \tag{12}$$

The constant q in (12) can be numerically different from q in (10), but the same symbol is used here for simplicity.

Processing of lg channel

The output from lg channels, x_j , is assumed to be proportional to ground-motion acceleration.

Acceleration

To remove the base-line offset, the high-pass filter H1 is applied to compute acceleration as follows.

$$a_j = \frac{1+q}{2} \frac{x_j - x_{j-1}}{g_{lg}} + q a_{j-1} \tag{13}$$

where g_{lg} is the gain factor for the accelerograph.

Wood-Anderson Response

The Wood-Anderson response, w_j , is computed using the difference equation for acceleration input

$$(w_j - 2w_{j-1} + w_{j-2}) / \Delta t^2 + 2hw_0 (w_j - w_{j-1}) / \Delta t + w_0^2 w_j = g_{wa} a_j \tag{14}$$

The corresponding recursive filter is given by,

$$w_j = \frac{1}{c_2} \left[g_{wa} \Delta t^2 a_j + 2c_1 w_{j-1} - w_{j-2} \right] \tag{15}$$

The constants c_1 and c_2 are given by (4) and (5)

The transfer function corresponding to (15) is

$$G(w) = \Delta t^2 g_{wa} \frac{1}{c_2 - 2c_1 e^{-iw\Delta t} + e^{-2iw\Delta t}} \quad (16)$$

The filter constants were adjusted by minimizing the difference between $|G(w)|$ and the corresponding analytic response in the least square sense. The adjusted constants are given in Table 1 The error is less than 3 % over the frequency band of 0.01 to 10 Hz, as shown in Figure 6.

Narrow-band Response for Computation of Response Spectral Amplitudes

The computation is the same as that for the Wood-Anderson response, and the adjusted constants are given in Table 1. The error is less than 3 % over the frequency band of 0.01 to 10 Hz, as shown in Figure 7.

Velocity

The velocity is obtained by integration and high-pass filtering with H1:

$$v_j = \frac{1+q}{2} \frac{a_j + a_{j-1}}{2} \Delta t + q v_{j-1} \quad (17)$$

The high-pass filter is applied to remove the long-term drift of the velocity trace caused by integration.

Energy and Displacement

The computation of energy and displacement from velocity is the same as that for vbb channel (equations 11 and 12).

Overall Response

The overall responses for acceleration, velocity, and displacement for vbb channel (Dt=0.05 sec), vsp channel (Dt=0.01 sec), and lg channel (Dt=0.01 sec) are shown in Figures 8, 9, and 10, respectively. The response is relative to the theoretical response, and q=0.998 is used. Except for the acceleration response for vbb channel, the error is negligible. Since accelerations for large events are usually measured on lg channels, the error in the acceleration measured on vbb channels is insignificant. The roll-off at high frequencies is due to the finite-difference differentiation and integration used in (1), (12) and (17), and the roll-off at lower frequencies is due to the high-pass filter H1. The roll-off at low frequencies can be adjusted, if so desired, by changing the value of q, as shown in Figure 5.

Stability

Since recursive filters can become unstable (Hamming, 1989, Scherbaum, 1996), we examined the stability of the filters used for the Wood-Anderson response, and the narrow-band response.

For $|h|<1$, the denominator of the transfer functions (6) and (16) can be written as $(z-p_1)(z-p_1^*)$, where $z=e^{-iw\Delta t}$ and p_1 is a pole given by

$$p_1=(1+hw_0\Delta t)+iw_0\Delta t\sqrt{1-h^2} \tag{18}$$

and p_1^* is the complex conjugate of p_1. For the filter to be stable, $|p_1|$ must be larger than 1, which leads to

$$1>h>-w_0\Delta t/2 \tag{19}$$

All the values of h in the Table 1 satisfy this condition, and the recursive filters used here are stable.

Comparison of wave forms

For the overall comparison between the results obtained with the recursive filters and with the traditional frequency-domain method, we show the comparisons of the Wood-Anderson responses, and the response functions for T_0=0.3, 1.0 and 3.0 sec in Figures 11, 12, 13, and 14. The wave forms are almost indistinguishable between the responses computed with the recursive filters for vbb, vsp and lg channels and those computed using the traditional frequency domain method.

We note that although the filter constants were determined by fitting only the amplitude of the transfer functions, the good match of the wave forms indicates that the phase response is also matched well.

Conclusion

The use of recursive time domain filters to compute ground-motion parameters streamlines the operation of a seismic network, thereby enhancing the reliability and robustness of the network during a major earthquake. Relatively simple recursive filters accomplish this objective. The method will find useful applications in other networks with similar objectives, and in building dataloggers with a capability of providing various types of amplitude parameters such as acceleration, velocity, displacement, energy, Wood-Anderson response, and response spectral amplitudes as an output. Such dataloggers will have broad applications for real-time ground-motion monitoring networks.

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Table 1

For vbb channel with Dt=0.05 sec

	f_0(Hz) (T_0(sec))	h	g
W-A	1.39 (0.719)	0.568	3110
RS T=0.3 sec	3.26 (0.307)	-0.461	0.875
RS T=1.0 sec	1.00 (1.00)	-0.108	0.988
RS T=3.0 sec	0.333 (3.00)	-0.021	0.986

For vbb channel with Dt=0.0125 sec

	f_0(Hz) (T_0(sec))	h	g
W-A	1.30 (0.769)	0.774	2999
RS T=0.3 sec	3.35 (0.299)	-0.0868	0.990
RS T=1.0 sec	1.00 (1.00)	0.00629	0.998
RS T=3.0 sec	0.334 (2.99)	0.0440	0.998

For vbb channel with Dt=0.01 sec

	f_0(Hz) (T_0(sec))	h	g
W-A	1.29 (0.775)	0.781	2963
RS T=0.3 sec	3.34 (0.299)	-0.0583	0.996
RS T=1.0 sec	1.00 (1.00)	0.0160	0.988
RS T=3.0 sec	0.334 (2.99)	0.0440	0.999

For lg channel with Dt=0.0125 sec

	f_0(Hz) (T_0(sec))	h	g
W-A	1.30 (0.769)	0.774	2999
RS T=0.3 sec	3.34 (0.299)	-0.0800	1.00
RS T=1.0 sec	1.00 (1.00)	0.0100	1.00
RS T=3.0 sec	0.334 (2.99)	0.0430	1.00

For lg channel with Dt=0.01 sec

	f_0(Hz) (T_0(sec))	h	g
W-A	1.29 (0.775)	0.781	2963
RS T=0.3 sec	3.34 (0.299)	-0.0541	1.00
RS T=1.0 sec	1.00 (1.00)	0.0180	1.00
RS T=3.0 sec	0.334 (2.99)	0.0440	1.00

Figure 1

Relative Wood-Anderson response (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from vbb channel with a sampling interval (Dt) of 0.05 sec. Note the large difference of the period T_0, damping constant h, and the gain factor g from those of the actual instrument (0.8, 0.8, and 2800, respectively).

Figure 2

Relative Wood-Anderson response (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from vsp channel with Dt=0.01 sec. Note the difference of the period T_0, damping constant h, and the gain factor g from those of the actual instrument.

Figure 3

Relative narrow band response at T_0=0.3 sec (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from vbb channel with Dt=0.05 sec. Note the negative damping constant h . Only the response near 0.33 Hz is relevant.

Figure 4

Relative narrow band response at T_0=0.3 sec (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from vsp channel with Dt=0.01 sec Note the negative damping constant h

Figure 5

Response of the recursive high-pass filter (H1) as a function of wDt for three values of q.

Figure 6

Relative Wood-Anderson response (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from lg channel with a sampling interval Dt=0.01 sec

Figure 7

Relative narrow band response at T_0=0.3 sec (i.e. ratio of the response computed with a recursive filter to the analytic response) computed from lg channel with Dt=0.01 sec. Note the negative damping constant h

Figure 8

The relative response of acceleration, velocity and displacement computed with a recursive filter applied to vbb channel with Dt=0.05 sec.

Figure 9

The relative response of acceleration, velocity and displacement computed with a recursive filter applied to vsp channel with Dt=0.01 sec.

Figure 10

The relative response of acceleration, velocity and displacement computed with a recursive filter applied to lg channel with Dt=0.01 sec.

Figure 11

Comparison of the Wood Anderson response computed with the traditional frequency domain method (Freq. D.), with a recursive filter applied to lg channel (LG), vsp channel (VSP), and vbb channel (VBB). The record used is the E-W component of the seismogram of a M_L=4.9 earthquake in Northridge which occurred on April 26, 1997, and was recorded at Pasadena.

Figure 12

Comparison of the narrow-band response at T_0=0.3 sec computed with the traditional frequency domain method (Freq. D.), with a recursive filter applied to lg channel (LG), vsp channel (VSP), and vbb channel (VBB).

Figure 13

Comparison of the Wood Anderson response at T_0=1.0 sec computed with the traditional frequency domain method (Freq. D.), with a recursive filter applied to lg channel (LG), vsp channel (VSP), and vbb channel (VBB).

Figure 14

Comparison of the Wood Anderson response at T_0=3.0 sec computed with the traditional frequency domain method (Freq. D.), with a recursive filter applied to lg channel (LG), vsp channel (VSP), and vbb channel (VBB).

Publication

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Technical Abstract

We have developed a method to continuously monitor ground-motion parameters to minimize the impact of the sudden increase in the workload on a seismic network during a major earthquake. In this method, an earthquake is not treated as a special event, but is part of continuous perturbation of ground motion. The incoming continuous seismic data are processed with the use of various time-domain recursive filters to compute ground-motion

velocity, acceleration, energy, Wood-Anderson seismograms, and narrow-band responses at 0.3, 1.0 and 3.0 sec which are used for computation of response spectral amplitudes. The continuous time-domain method has advantage over the traditional frequency-domain method for streamlining the operation of a seismic network, especially during a complex seismic sequence. The method has been tested in the Southern California Digital Seismic Network (e.g. TERRAscope and TriNet) for nearly 2 years, and is used for real-time magnitude and ground-motion amplitude reporting purposes. If the method is implemented in the individual datalogger at every field station, it would be possible to telemeter desired amplitude information (acceleration, velocity, displacement, Wood-Anderson, spectral responses etc.) with sufficient accuracy from a field station to the network center through a relatively slow communication line (e.g. regular digital telephone line).

Non-technical Summary

As modern broad-band and wide dynamic range seismic instruments have become widely available, real-time monitoring of earthquake ground motion is becoming an important function of a seismic network for earthquake hazard mitigation purposes Important amplitude parameters include acceleration, velocity, displacement, energy, etc. Traditionally, most seismic networks operate in "trigger" mode. Computation of amplitude parameters is initiated only when a significant seismic event is detected. In this mode, the work-load on the system increases suddenly during a major earthquake, which could cause a system failure during the time when real-time data are most needed for emergency services. To alleviate this problem, we developed a "continuous" monitoring method which continuously computes ground-motion parameters regardless of whether earthquakes are occurring or not; an earthquake is not treated as a special event, but is part of continuous perturbation of ground motion. This minimizes the fluctuation of work-load, and assures more reliable overall operation of the system. This is a simple conceptual change, but we believe that it would lead to a significant improvement in seismic network operation in the future. This method will be useful for the development of a new type of data recording system suitable for early warning system.