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Continuous Monitoring of Ground-Motion Parameters

by Hiroo Kanamori, Philip Maechling, and Egill Hauksson

Abstract We applied a time-domain method to continuously monitor ground-motion parameters to facilitate rapid determination of the geographical distribution of ground motion and earthquake parameters. This approach minimizes the impact of the sudden increase in the workload on data acquisition facilities and streamlines the operation of a seismic network, especially during a complex earthquake sequence. The incoming continuous time series is 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 method is implemented in the Southern California Digital Seismic Network. The method can be implemented at every field station, which would make it possible to process the time series locally and continuously telemeter desired amplitude parameters with sufficient accuracy from a field station to multiple users through a relatively low data-rate communication line (e.g., regular telephone line or limited bandwidth satellite link).

Introduction

As modern broadband and wide dynamic range seismic instruments have become widely available, real-time monitoring of earthquake ground motion is becoming an important function of regional seismic networks for earthquake hazard mitigation purposes. Relevant amplitude parameters include acceleration, velocity, displacement, energy, Wood–Anderson response, and 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 processing of data must wait until the recording of the trigger is completed. In addition, the workload 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 allow real-time processing and to alleviate the overload problem, we developed a continuous monitoring method that 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 workload 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.

The purpose of this article is to address some 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 data logger itself. Such a data logger can process data on site to compute desired amplitude parameters (acceleration, velocity, displacement, Wood–Anderson, and spectral responses, etc.) and send them to users. In this case, because the computed amplitude parameters can be sent at a relatively slow rate (e.g., 1 sample/sec), even a relatively slow communication line (e.g., regular digital telephone line) would be adequate. This would allow for easy simultaneous reception of the desired information at multiple locations to avoid a single point failure of the system.

We have tested the method on-line in the Southern California Digital Seismic Network (e.g., TERRAscope and TriNet) for nearly 2 yr. This continuous system is currently used for on-line magnitude reporting and for broadcasting ground-motion data (acceleration and velocity) through our web site: www.trinet.org as ShakeMap (Wald *et al.*, 1999).

In the following, we describe the method applied to broadband instruments and strong-motion accelerographs. The broadband instruments used here are Streckeisen STS-1, STS-2, and Guralp CMG-40T seismometers, and the strong-motion instrument is a Kinemetrics FBA-1 accelerograph. The method should be applicable to other instruments with similar characteristics. The broadband channel with a sampling interval (Δt) of 0.05 sec is called the vbb channel, and that with either $\Delta t = 0.0125$ or 0.01 sec is called the vsp channel. The acceleration channel with either $\Delta t = 0.0125$ or 0.01 sec is called the lg (low-gain) channel.

In the TriNet application, since the filters need to be applied on-line to a large number of channels, 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 data logger.

Processing of the vbb and vsp Channels

The output from the instrument is assumed to be proportional to ground-motion velocity over the frequency band of our interest.

Acceleration

The acceleration a_j is computed simply by

$$a_j = (\zeta_j - \zeta_{j-1})/(g\Delta t), \tag{1}$$

where ζ_j is the output from either the vbb or the vsp channel, Δt is the sampling interval, and g is the gain factor. This simple diffentiator is adequate for most of our purposes, but it is not accurate at frequencies higher than ½ Nyquist frequency. If higher accuracy is desired, the recursive differentiator (Rabiner and Steiglitz, 1970)

$$\begin{aligned} a_j = {} & (1.1509967359\zeta_j - 0.3788779578\zeta_{j-1} \\ & - 0.7721187782\zeta_{j-2})/(g\Delta t) \\ & - 0.8593897a_{j-1} + 0.1021010570a_{j-2} \end{aligned} \tag{1'}$$

should be used instead. In our application, we use (1) for simplicity.

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,

$$\begin{aligned} (w_j - 2w_{j-1} + w_{j-2})/\Delta t^2 + 2h\omega_0(w_j - w_{j-1})/\Delta t \\ + \omega_0^2 w_j = (g_{wa}/g)(\zeta_j - \zeta_{j-1})/\Delta t \end{aligned} \tag{2}$$

where h, ω_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

$$w_j = \frac{1}{c_2}[(g_{wa}/g)\Delta t(\zeta_j - \zeta_{j-1}) + 2c_1 w_{j-1} - w_{j-2}], \tag{3}$$

where

$$c_1 = 1 + h\omega_0\Delta t \tag{4}$$

and

$$c_2 = 1 + 2h\omega_0\Delta t + (\omega_0\Delta t)^2. \tag{5}$$

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

$$F(\omega) = \Delta t\left(\frac{g_{wa}}{g}\right)\frac{1 - e^{-i\omega\Delta t}}{c_2 - 2c_1 e^{-i\omega\Delta t} + e^{-2i\omega\Delta t}}. \tag{6}$$

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

$$F_0(\omega) = \left(\frac{g_{wc}}{g}\right)\frac{i\omega}{\omega_0^2 - 2ih\omega_0 - \omega^2}. \tag{7}$$

For the standard Wood–Anderson instrument, $h = 0.8$, $\omega_0 = 2\pi/0.8\ \text{sec}^{-1}$, $g_{wa} = 2800$ (Richter, 1958). However, because of the use of the difference equation with a finite Δt (0.05 sec), the response calculated from (6) is not accurate. This error (difference between equations 6 and 7) decreases as Δt decreases. To minimize the error, these constants are adjusted in the least-squares sense (minimize $(|F(\omega)| - |F_0(\omega)|)^2$), so that the error in the overall response is less than 5% over the frequency band of 0.05 to 6.5 Hz for the 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 the vsp

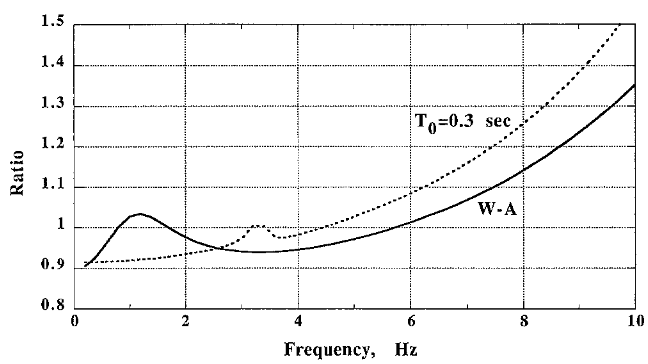

Figure 1. Relative Wood–Anderson response (i.e., ratio of the response computed with a recursive filter to the analytic response) computed from the vbb channel with a sampling interval (Δt) of 0.05 sec (solid curve). The constants used are $T_0 = 0.719$ sec, $h = 0.568$, and $g_{wa} = 3110$. Note the large difference of the period T_0, damping constant h, and the gain factor g_{wa} from those of the actual instrument (0.8, 0.8, and 2800, respectively). Relative narrow-band response at $T_0 = 0.3$ sec computed from the vbb channel with $\Delta t = 0.05$ sec (dotted curve). The constants used are $T_0 = 0.307$ sec, $h = -0.461$, and $g = 0.875$. Note the negative damping constant h. Only the response near 3.3 Hz is relevant.

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 ω_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 $T_0(2\pi/\omega_0) = 0.3$, 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-squares 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 the vbb channel, and to -0.0583 for the 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 response of the vbb channel at $T_0 = 0.3$ sec is shown in Figure 1. Because the response is very narrow band, the large error at $f \geqq 6$ Hz is of little consequence. The response for the vsp channel is accurately computed with the adjusted constants (errors are less than 1%). 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 following form (x_j: input; y_j: output):

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

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

$$\mathrm{H1}(\omega) = \frac{1 + q}{2}\,\frac{1 - e^{-i\omega\Delta t}}{1 - qe^{-i\omega\Delta t}}. \tag{9}$$

If $q = 0.998$, the response is less than 0.8 at periods longer than 116 and 23 sec for $\Delta t = 0.05$ and $\Delta t = 0.01$ sec, respectively.

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

$$v_j = \frac{1 + q}{2}\,\frac{\zeta_j - \zeta_{j-1}}{g} + qv_{j-1}, \tag{10}$$

where ζ_j is the output from the vbb or vsp channel.

Energy (integral of velocity squared)

The energy, e_j, is computed from velocity by

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

Because 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

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

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

Table 1
Adjusted Constants for the vbb, vsp, and lg Channels

	For the vbb Channel with $\Delta t = 0.05$ sec			For the vsp Channel with $\Delta t = 0.01$ sec			For the lg Channel with $\Delta t = 0.01$ sec		
	f_0 (Hz) (T_0, sec)	h	g	f_0 (Hz) (T_0, sec)	h	g	f_0 (Hz) (T_0, sec)	h	g
W-A	1.39 (0.719)	0.568	3110	1.29 (0.775)	0.781	2963	1.29 (0.775)	0.781	2963
RS $T = 0.3$ sec	3.26 (0.307)	−0.461	0.875	3.34 (0.299)	−0.0583	0.996	3.34 (0.299)	−0.0541	1.00
RS $T = 1.0$ sec	1.00 (1.00)	−0.108	0.988	1.00 (1.00)	0.0160	0.988	1.00 (1.00)	0.0180	1.00
RS $T = 3.0$ sec	0.333 (3.00)	−0.021	0.986	0.334 (2.99)	0.0440	0.999	0.334 (2.99)	0.0440	1.00

Processing of the lg Channel

The output from lg channels, ξ_j, is assumed to be proportional to ground-motion acceleration over the frequency band of our interest.

Acceleration

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

$$a_j = \frac{1+q}{2}\frac{\xi_j - \xi_{j-1}}{g_{lg}} + qa_{j-1} \qquad (13)$$

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:

$$(w_j - 2w_{j-1} + w_{j-2})/\Delta t^2 + 2h\omega_0(w_j - w_{j-1})/\Delta t + \omega_0^2 w_j = g_{wa}a_j. \qquad (14)$$

The corresponding recursive filter is given by

$$w_j = \frac{1}{c_2}[g_{wa}\Delta t^2 a_j + 2c_1 w_{j-1} - w_{j-2}]. \qquad (15)$$

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

The transfer function corresponding to (15) is

$$G(\omega) = \Delta t^2 g_{wa}\frac{1}{c_2 - 2c_1 e^{-i\omega\Delta t} + e^{-2i\omega\Delta t}}. \qquad (16)$$

The filter constants were adjusted by minimizing the difference between $|G(\omega)|$ and the corresponding analytic response in the least-squares 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.

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.

Velocity

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

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

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 the vbb channel (equations 11 and 12).

Overall Response

The overall responses for acceleration, velocity, and displacement for the vbb channel ($\Delta t = 0.05$ sec), vsp channel ($\Delta t = 0.01$ sec), and lg channel ($\Delta t = 0.01$ sec) are shown in Figures 2a, 2b, and 2c, respectively. The response is relative to the theoretical response, and $q = 0.998$ is used. Except for the acceleration response for the vbb channel, the

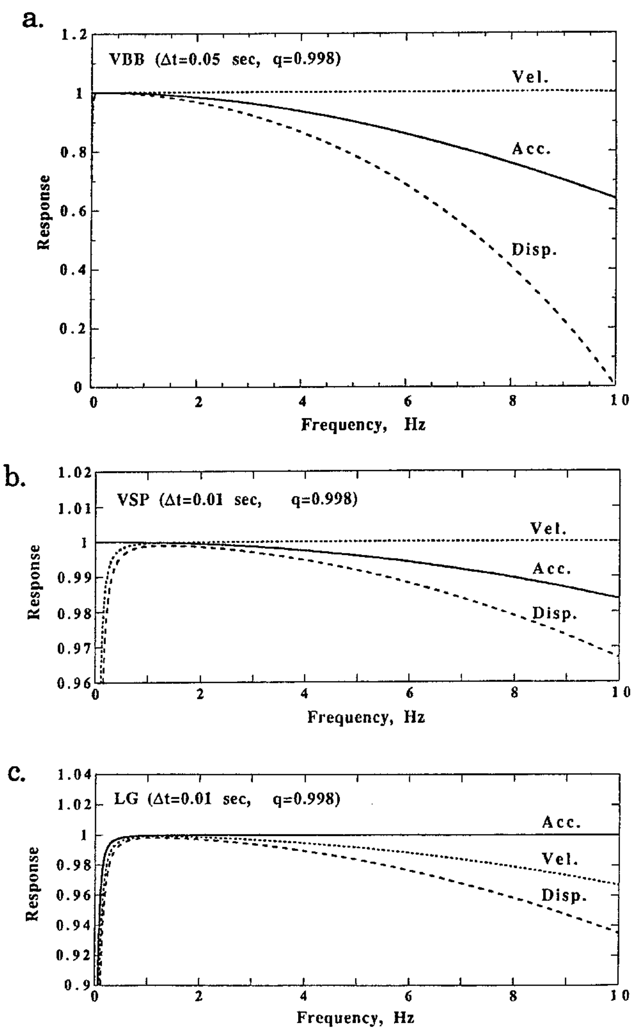

Figure 2. (a) The relative response of acceleration, velocity, and displacement computed with a recursive filter applied to the vbb channel with $\Delta t = 0.05$ sec. (b) The relative response of acceleration, velocity, and displacement computed with a recursive filter applied to the vsp channel with $\Delta t = 0.01$ sec. (c) The relative response of acceleration, velocity, and displacement computed with a recursive filter applied to the lg channel with $\Delta t = 0.01$ sec.

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. If higher accuracy is desired for acceleration computed from vbb channels, equation (1′) should be used instead of (1).

Stability

Because 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 $z = e^{-i\omega\Delta t}$ and p_1 is a pole given by

$$p_1 = (1 + h\omega_0\Delta t) + i\omega_0\Delta t\sqrt{1 - h^2} \qquad (18)$$

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

$$1 > h > -\omega_0\Delta t/2. \qquad (19)$$

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

Comparison of Waveforms

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 $T_0 = 1.0$ sec in Figures 3 and 4. The wave forms are almost indistinguishable between the responses computed with the recursive filters for the 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 waveforms indicates that the phase response is also matched well.

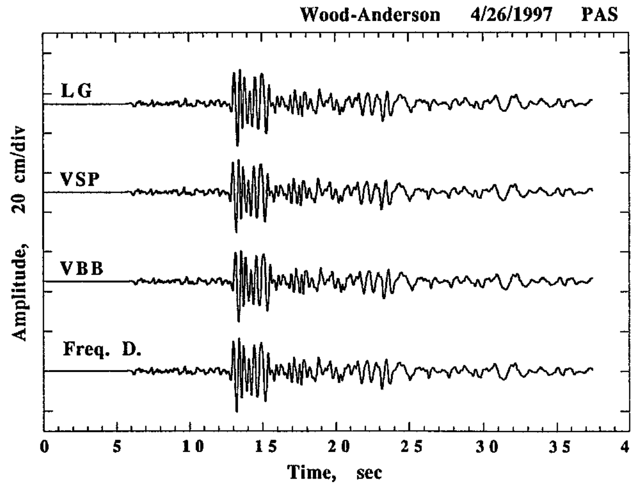

Figure 3. Comparison of the Wood–Anderson response computed with the traditional frequency-domain method (Freq. D.), with a recursive filter applied to the lg channel (LG), vsp channel (VSP), and vbb channel (VBB). The record used is the E–W component of the seismogram of an $M_L = 4.9$ earthquake in Northridge that occurred on 26 April 1997 and was recorded at Pasadena.

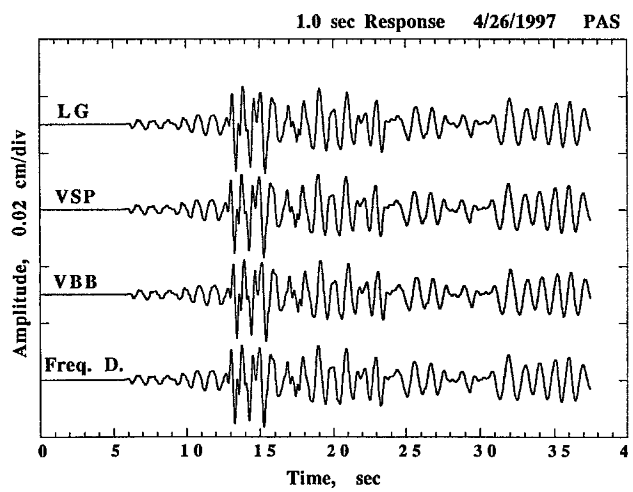

Figure 4. Comparison of the Wood–Anderson response at $T_0 = 1.0$ sec computed with the traditional frequency-domain method (Freq. D.), with a recursive filter applied to the lg channel (LG), vsp channel (VSP), and vbb channel (VBB).

Conclusion

The use of continuous method 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 data loggers 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 data loggers will have broad applications for real-time ground-motion monitoring networks.

Acknowledgments

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Seismological Laboratory
California Institute of Technology
Pasadena, California 91125

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