On the Analysis of "Weak" Strong Motion Data

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Abstract

The limited "strong motion" data sets for the populated regions of southwestern British Columbia consist of "weak" ground motions (0.1-5.7% gravity(g)) of relatively short duration (waveforms of 7-30 s total duration). For the most recent strong motion data sets (recorded during 1996-1997), several of the waveforms are just above the bit-level noise. In this manuscript low-level, short-duration signals are considered to aid in the interpretation of these data sets. The frequency range of the "weak" strong motion data that can be interpreted with confidence is examined by using the recordings of two moderate earthquakes made on three-component broadband and strong motion instruments that are co-located in the seismic vault at the Pacific Geoscience Centre on southern Vancouver Island. This comparison shows that even very low-amplitude (0.1-0.5%g) digital strong motion waveforms provide a true representation of the ground motion. A comparison of the spectrum shows that low-level (peak amplitudes > 0.2%g) and relatively short duration (15 s duration signal and longer) signals are in good agreement (typically within a few percent) with those of broadband data, over the frequency range 0.5-15 Hz. For the lower amplitude recordings (< 0.2%g) and shorter duration signals (7 s) the spectral shapes are still in good agreement with the broadband data, but spectral amplitudes from the strong motion waveforms may be underestimated. This study demonstrates the usefulness of very low-amplitude, digital strong motion data that being collected at an ever-increasing rate.

Introduction

Recent studies have demonstrated the usefulness of weak-motion recordings in the assessment of local site response (e.g., Hartzell et al. 1996; Meremonte et al. 1996).

The only significant strong motion data sets collected, to date, in the populated regions of southwestern British Columbia, consist of "weak" ground motions ranging from 0.1 to 5.7% gravity (g) and relatively short duration (7-30 s) signal lengths. These data sets (see Figure 1) are: 1) the M_W=5.3 1976 Pender Island earthquake, located 50 km to the SSE of Vancouver (recorded at 6 sites); 2) the M_W=5.1 1996 Duvall, Washington earthquake, located 180 km to the SE of Vancouver (recorded at 9 sites), and 3) the M_W=4.3 1997 Georgia Strait earthquake located 37 km to the west of Vancouver (recorded at 21 sites). The latter two events were both shallow, thrust events. The 1976 earthquake was a normal faulting event in the subducting Juan de Fuca plate at a depth of 62 km. Basic information (e.g., maximum ground acceleration, epicentral distance range, and signal durations) for the complete data sets are given in Table 1. For details on these data sets, see Weichert and Milne (1980), Weichert et al. (1996), and Cassidy et al. (1998). Interpretations of these data are presented in Cassidy et al. (1997), Rogers et al. (1998), Cassidy and Rogers (1999), and Atkinson and Cassidy (1999). Most of the waveforms in these three data sets are between 15 and 20 s duration, although some of the 1976 waveforms are as short as 7 s duration. All of these waveforms represent "weak" ground shaking, with peak accelerations ranging from 0.1%g to 5.7%g. Several of the waveforms in the Duvall and Georgia Strait data sets are extremely low-amplitude recordings, just above the bit-level noise. For the latter, it is not obvious that these data will be useful. For example, some questions are:

1) do very low-amplitude (e.g., approaching the bit level noise) recordings from strong motion seismographs adequately represent the true ground motion?
2) what frequency range is useful, and resolvable in these "weak" strong motion recordings?

3) what frequency range can be resolved in short duration (7-10 s) recordings?

Here, these questions are addressed by comparing the strong motion recordings of the 1996 and 1997 earthquakes made at PGC (on southern Vancouver Island) with the well-defined recordings of these earthquakes made on a co-located 3-component broadband seismograph. Three-component strong motion recordings of these earthquakes made at site KID on the Fraser River Delta are utilised to examine the effects of signal duration.

The Data

Instrument Parameters

The waveforms considered in this study are the E-W, N-S, and vertical component strong motion and broadband recordings made at the seismic vault situated on bedrock at PGC, and strong motion waveforms from the soil site KID (for details see Weichert et al. (1996), and Cassidy et al. (1998)). The PGC strong motion data are from a Kinemetrics SSA-1 instrument. This is a 2-g sensor, with a natural frequency of 50 Hz. The trigger threshold was set to 0.1%g, and the sample rate was 200 Hz. This instrument is flat in acceleration to 50 Hz. The bit level recording for this instrument is 0.48 cm/s^2 (or 0.05%g). The PGC broadband seismograph uses a CMG3-ESP and records continuously at a sample rate of 40 Hz. This instrument is flat in velocity from 30 s period to 50 Hz (beyond the 20 Hz Nyquist frequency of the digitiser), and has a maximum acceleration recording (clipping) level of 0.9%g to 9%g over the frequency range of 1 Hz to 10 Hz.

The KID strong motion data used in this study were recorded on a Kinemetrics SSA-2 2g sensor with a natural frequency of 200 Hz. This instrument, operated by BC Hydro had a trigger threshold of 0.4%g and operated at a sample rate of 200 Hz.

Data Records

The waveforms used in this study are PGC and KID recordings of the 1996 Duvall earthquake (Weichert et al., 1996) and PGC recordings of the 1997 Georgia Strait earthquake (Cassidy et al., 1998). The PGC recordings of the Duvall earthquake (epicentral distance of 155 km) have a peak acceleration of 1.8-4.6 cm/s^2 (0.18-0.47%g); for the Georgia Strait earthquake (epicentral distance of 67 km) the PGC peak acceleration ranges from 1.0-1.9 cm/s^2 (0.1-0.2%g). The KID recordings of the Duvall earthquake (epicentral distance 186 km) have a peak acceleration of 2.9-14.3 cm/s^2 (0.3-1.5%g).

Waveform Comparisons

Initially, the three-component strong-motion and broadband acceleration waveforms recorded on instruments co-located in the seismic vault at PGC are compared. The strong motion recordings are acceleration waveforms from an SSA-1 instrument. The only processing applied to these records was the removal of the DC offset. There was no need to correct these waveforms for instrument response over the frequency range of interest in this study (0.1-20 Hz) - as the SSA-1 response is flat to about 50 Hz. The broadband recordings were processed as follows: 1) the DC offset was removed from the traces; 2) the instrument response was removed; and 3) the records were differentiated to obtain ground acceleration records.

The PGC three-component strong motion and broadband acceleration records (processed as described above) of the 1996 Duvall, Washington earthquake are compared in Figure 2. Despite the very low amplitudes of the strong motion recordings (the bit-level noise is apparent in all three components), the records are remarkably similar - as demonstrated in the close-ups (Figure 2b) of the pre-signal noise and the S-waveform. The signal-to-noise ratio (SNR - the ratio of the peak signal amplitude to that of the bit-level noise) for the strong motion records is 9.6

(N-S component), 7.4 (E-W component), and 3.7 (for the vertical component). The corresponding peak acceleration for the three components is 0.47%g (N-S), 0.36%g (E-W), and 0.18%g (Z).

A comparison of the strong motion and broadband recordings of the 1997 Georgia Strait earthquake is presented in Figure 3. For this example the strong motion records are of lower amplitude, with signal-to-noise ratios (as described above) of 4.0 (for the N-S component), 2.6 (E-W component), and 2.1 (for the vertical component). The corresponding peak accelerations are 0.19%g (N-S), 0.12%g (E-W), and 0.10%g (Z). Despite the extremely low amplitudes of these strong motion records, the waveforms are also in very good agreement with the broadband recordings (Figure 3b) of the ground motion at this site.

The results of the waveform comparisons for these two earthquakes demonstrates that: 1) extremely low-amplitude (just above the bit-level noise) strong motion records adequately represent the true ground shaking; and 2) broadband seismograms from the Canadian National Seismograph Network (CNSN) can easily be converted into ground acceleration records.

Spectral Comparison

The Fourier amplitude spectra for the time-series records shown in the previous section are computed and illustrated in Figure 4 (Duvall earthquake) and Figure 5 (Georgia Strait earthquake). The spectra were computed using the 30-second-long traces shown in Figures 2a and 3a. In Figures 4 and 5 both the unfiltered spectra and smoothed spectra (running mean filter of 0.5-Hz width) are shown on the left, and right, respectively.

For the Duvall earthquake, the strong motion spectra are remarkably similar to the broadband spectra for all three components. The slight differences in the spectral amplitudes near 18-20 Hz result from differences in the sample rates of the two data sets. The broadband data are sampled at 40 Hz, and hence the Nyquist frequency is at 20 Hz; whereas the strong motion data are sampled at 200 Hz and have a Nyquist frequency of 100 Hz. Over the frequency range of 0.5-15 Hz, the "weak" strong motion spectral amplitudes are within a few percent (maximum difference of about 12% on the E-W component) of the levels determined from the broadband recordings.

For the Georgia Strait earthquake, the PGC strong motion spectra are again similar to those of the broadband spectra (Figure 5). However, in this case there are some differences. Over the frequency range of 2-10 Hz the spectral amplitudes determined from the "weak" strong motion data are typically 10-15% less than those determined from the broadband recordings, and at some frequencies are as much as 30% lower. At frequencies less than 1-1.5 Hz the strong motion spectral amplitudes are consistently higher than those from the broadband data. Also, there is a distinct peak in the E-W component of the unfiltered strong motion spectrum. This is attributed to the "square-wave" bit-level noise visible in Figure 3a (bottom trace) - that although of very low-amplitude, is nonetheless significant in the case of an extremely low-amplitude recording.

Frequency Content

The frequency content of earthquake waveforms depends on several factors, including: 1) the earthquake source spectra (e.g., larger earthquakes yield more long-period energy); 2) epicentral distance (high-frequency waves are attenuated more rapidly with distance than are low-frequency waves); and 3) local soil conditions (depending on the velocity and thickness, soil layers may cause resonance or amplification at some frequencies). To isolate the effect of the local soil conditions one must first consider the earthquake source and propagation effects. Under ideal circumstances, a bedrock 3-component recording will be available in the immediate vicinity of the soil site of interest, thus allowing the traditional spectral ratio technique (Borcherdt, 1970) to be applied. If there are no bedrock recordings in the immediate vicinity of the soil site of interest, the input waveform to the soil site may be estimated using either single-component, or 3-component regional seismograph data (Atkinson and Cassidy, 2000).

It should be noted that the frequency range that is of interest in designing common structures (1-20 storey) is about 0.5-10 Hz (or 0.1-2 s period). As is demonstrated in Figure 5, even moderate (magnitude 4.3-5.1) earthquakes contain a significant amount of energy in this passband. In Figure 6, the KID recording of the M=5.1 Duvall earthquake is shown. The top trace is the unfiltered waveform, the lower traces are low-pass filtered waveforms (with filter corner frequencies ranging from 5 Hz to 0.1 Hz). The panel on the left uses a fixed amplitude scale for all traces, the panel on the right shows traces normalized to their peak amplitude. By comparing the top three traces (all frequencies, less than 5 Hz, and less than 2 Hz), it is obvious that most of the energy in this signal is at frequencies between 2 and 5 Hz. However, there is still clearly resolvable signal near 1 Hz, and near 0.5 Hz (note in the right panel that the signal to noise ratio is still at least 2 for the 0.5 Hz low-pass filtered waveform). However, at frequencies of 0.1 Hz and lower there is no obvious signal in the waveform for this M=5.1 earthquake.

The unfiltered Fourier amplitude spectra for this waveform is shown in Figure 7. This clearly shows: 1) the peak in energy between 2-5 Hz, and 2) that there is resolvable energy in this signal over the frequency range of 1-10 Hz (thus covering most of the engineering frequency range of interest).

Effects of Signal Duration

To examine the effect of signal duration on the estimation of the amplitude spectrum, we choose the longest duration recording and consider various signal-lengths. The 30 s duration recording of the 1997 Georgia Strait earthquake made at the site KID on the Fraser River delta near Vancouver is used to compute the Fourier amplitude spectrum (Figure 8). Note that the waveform consists of about 4.5 s of pre-event noise, the P-wave near 4.5 s, and the S-wave near 10 s. As indicated on the waveform, three signal durations are considered: the entire 30 s waveform; a 15-s window containing the S-wave and coda; and a 7-s window that includes the S-wave and coda. Note that a 15-s window is the most common signal-length for the strong motion data sets collected in western Canada to date, a 7-s window is the shortest duration waveform in the strong motion data set for the Pender Island earthquake.

The Fourier amplitude spectra obtained for these three time windows are shown in Figure 8 with two different smoothing levels; 0.1-Hz width (running mean filter); and 0.5-Hz width. The 0.1-Hz-filtered spectra shows that the 7-s duration window has greater variability in spectral amplitude (note the deeper troughs and the higher peaks) than the longer duration signal lengths. The 0.5-Hz-filtered spectra show nearly identical spectral amplitudes for the 15 s and 30 s windows and somewhat lower amplitudes (by about 25-30%) at some frequencies for the 7-s duration window compared to the 15-s and 30-s windows. Thus, short-duration windows ($\leq$7-s duration) should be interpreted with caution, particularly if one is interested in longer-period signals ($T>0.5$ s). However, the 15-s duration windows provide comparable resolution to the 30-s duration window over the frequency range examined here (0.5-20 Hz).

Discussion and Conclusions

In this manuscript “weak” (low-amplitude) strong motion recordings and broadband (mid-range amplitude) seismograph recordings of moderate earthquakes have been examined to determine the usefulness and potential limitations in the analysis and interpretation of very low-amplitude digital strong motion waveforms. Specifically, the following questions have been addressed:

1) do very low-amplitude (e.g., approaching the bit level noise) recordings from strong motion seismographs adequately represent the true ground motion?
2) what frequency range is useful, and resolvable in these "weak" strong motion recordings?
3) what frequency range can be resolved in short duration (7-10 s) recordings?

A comparison of very-low amplitude strong motion recordings with mid-range amplitude recordings obtained from co-located broadband instruments of two moderate earthquakes demonstrated that even for low-amplitude strong motion signals of 0.1-0.5%g (and signal amplitudes of only 2-10 times the bit level noise), the strong motion waveforms are in very good agreement with the mid-range amplitude broadband signals. A comparison of the Fourier amplitude spectra of the "weak" strong motion and broadband data showed that for strong motion amplitudes in the 0.2-0.5%g range (SNR of 3.7-9.6) also shows good agreement. The strong motion spectral amplitudes were within a few percent (maximum difference of 12% on one component) of the broadband amplitudes over the frequency range 0.5-15 Hz. However, for the Georgia Strait earthquake, the lower amplitude strong motion signals (0.1-0.2%g, or SNR of 2.0-4.0) exhibited a similar spectral shape to those obtained from the broadband data, but the strong motion spectral amplitudes were consistently lower (typically 10-15% less, but as large as 30% less) than the broadband amplitudes. Also, at frequencies lower than 1.5 Hz, the E-W strong-motion recording of the Georgia Strait earthquake (SNR of 2.6) was contaminated by instrument noise that restricts the use of the lower frequency signal.

Using signal-lengths ranging from 30-s to 7-s, the potential effects of signal duration on the estimation of amplitude spectra were examined. A 15-s duration signal length was found to provide a comparable result (over the entire frequency range of 0.1-20 Hz) to that of a 30-s duration window. This is important, as most of the strong motion waveforms collected in western

Canada are of 15 s duration. A 7-s duration signal showed the same spectral shape and characteristics, however the spectral amplitudes were reduced by 25-30% (relative to a 30-s window) at lower frequencies (frequency < 3-4 Hz). Thus, one needs to be cautious in interpreting short-duration (≤ 7 s) strong motion signals.

This comparison of broadband and low-amplitude strong motion waveforms demonstrates that "weak" (peak acceleration of less than 1%g) and relatively short-duration (15-s and longer) digital strong motion data can be utilised with confidence.

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Table 1. Information and Peak Accelerations for Strong Motion Data Sets in Southwest BC

Earthquake	Lat. °N Lon. °W	Mag. (M_W)	Dist. Range[1] (km)	Peak Acceleration E-W	 N-S	 Z (%g)	Signal Dur.[2] (s)	No.[3]
Pender Island	48.8 123.4	5.3	27-62	5.7	4.8	4.0	7-22	6
Duvall	47.76 121.88	5.1	137-186	1.5	1.2	0.4	15-33	9
Georgia Strait	49.24 123.62	4.3	33-87	2.4	2.4	1.5	10-30	21

[1] Epicentral distance range for complete data set

[2] Range of signal duration for complete data set

[3] Number of strong motion instruments that recorded this earthquake

Figure Captions

Fig. 1. Location map showing the epicenters and focal mechanisms of the 1997 M_W=4.3 Georgia Strait earthquake, the 1996 M_W=5.1 Duvall earthquake, and the 1976 M_W=5.3 Pender Island earthquake. Also shown is the location of the Fraser River delta (hatched area), the Vancouver Island bedrock site PGC, and the Fraser Delta soil site KID.

Fig. 2. a) Three-component strong motion (dotted) and broadband acceleration (solid) recordings of the Duvall earthquake made at PGC. Note that the bit level noise is apparent in the strong motion waveforms. b) close-ups of the pre-trigger noise (left) and S-wave (right).

Fig. 3. **a)** Three-component strong motion (dotted) and broadband acceleration (solid) recordings of the 1997 Georgia Strait earthquake made at PGC. Note that the bit level noise is apparent in the strong motion waveforms. b) close-ups of the pre-trigger noise (left) and S-wave (right).

Fig. 4. Unfiltered Fourier amplitude spectra (left) of the strong motion (dotted) and broadband (solid) waveforms (shown in Figure 2a) of the 1996 Duvall earthquake. The smoothed spectra (using a running mean filter of 0.5-Hz width) are shown on the right.

Fig. 5. Unfiltered Fourier amplitude spectra (left) of the strong motion (dotted) and broadband (solid) waveforms (shown in Figure 3a) of the 1997 Georgia Strait earthquake. The smoothed spectra (using a running mean filter of 0.5-Hz width) are shown on the right. Note the large spike near 0.8 Hz that contaminates the unfiltered E-W spectra (and the filtered E-W spectra at frequencies less than 1.5 Hz).

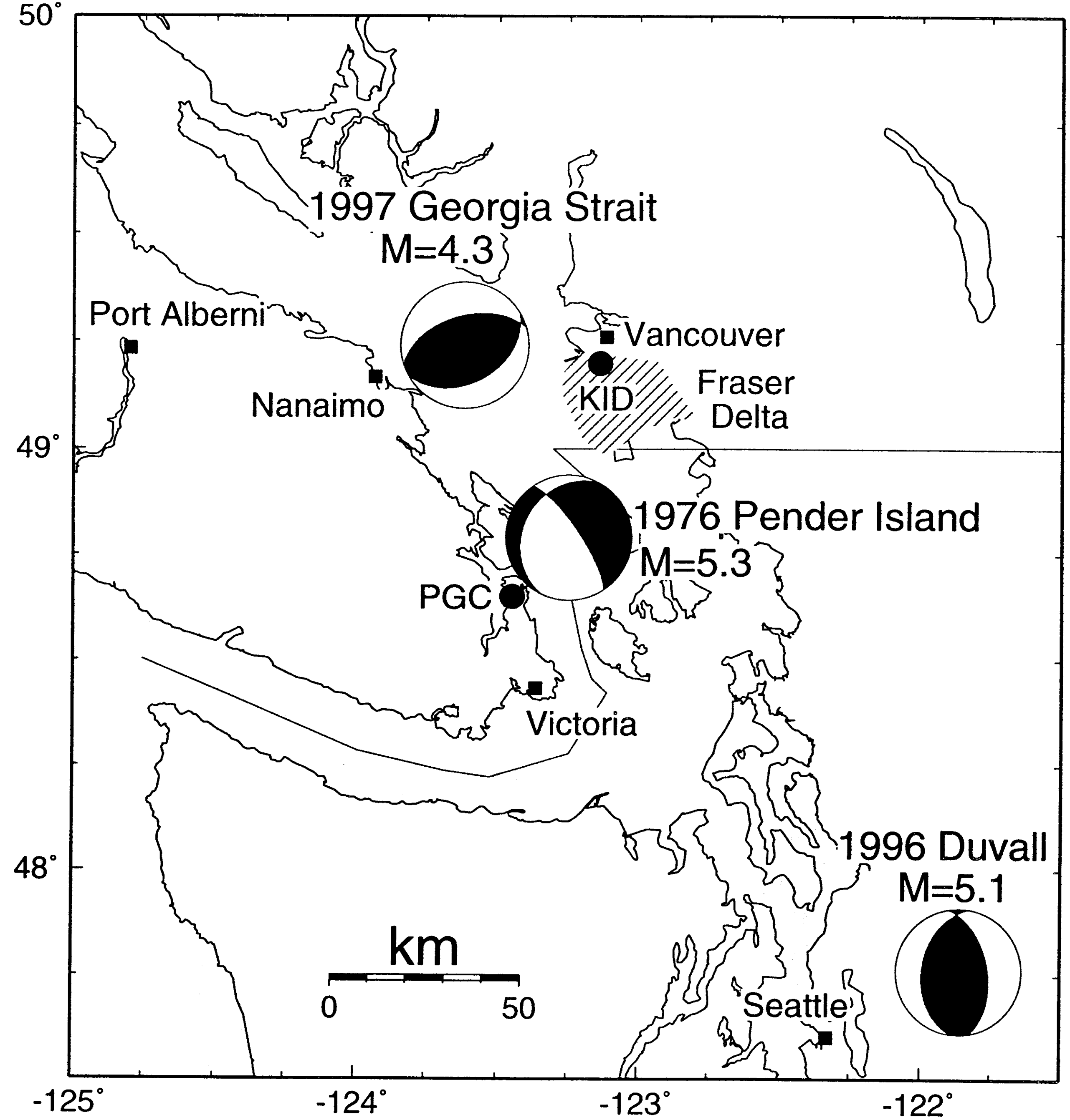
Fig. 6. KID L-component recording of the 1996 Duvall earthquake. Traces shown from top to bottom are unfiltered, and low-pass filtered with corner frequencies ranging from 5 Hz to 0.1 Hz, respectively. Traces on the left and right are the same; in the left panel the amplitude scale is fixed (-10 to +10 cm/s^2) and in the right panel the amplitude scale varies. Note that most of the energy is in the 2-5 Hz bandwidth, but that there is still resolvable energy at 0.5 Hz.

Fig. 7. Unfiltered acceleration spectra of the KID L-component waveform shown in Figure 6. Most of the energy is in the 2-5 Hz frequency range.

Fig. 8. KID L-component recording of the 1997 Georgia Strait earthquake (top) with the three signal duration window lengths considered in this study indicated. The arrival near 4 s is the P-wave, the arrival near 10 s is the S-wave. Filtered amplitude spectra (0.1 Hz smoothing shown on the left, and 0.5 Hz smoothing on the right) are compared for the three window lengths. The spectra of the 15 s and 30 s signals are in close agreement in both cases. The 7 s duration signal shows more variability than the longer duration signals (see text).

Fig. 1

Earthquake Locations



GMT Aug 4 09:23

Fig 2a

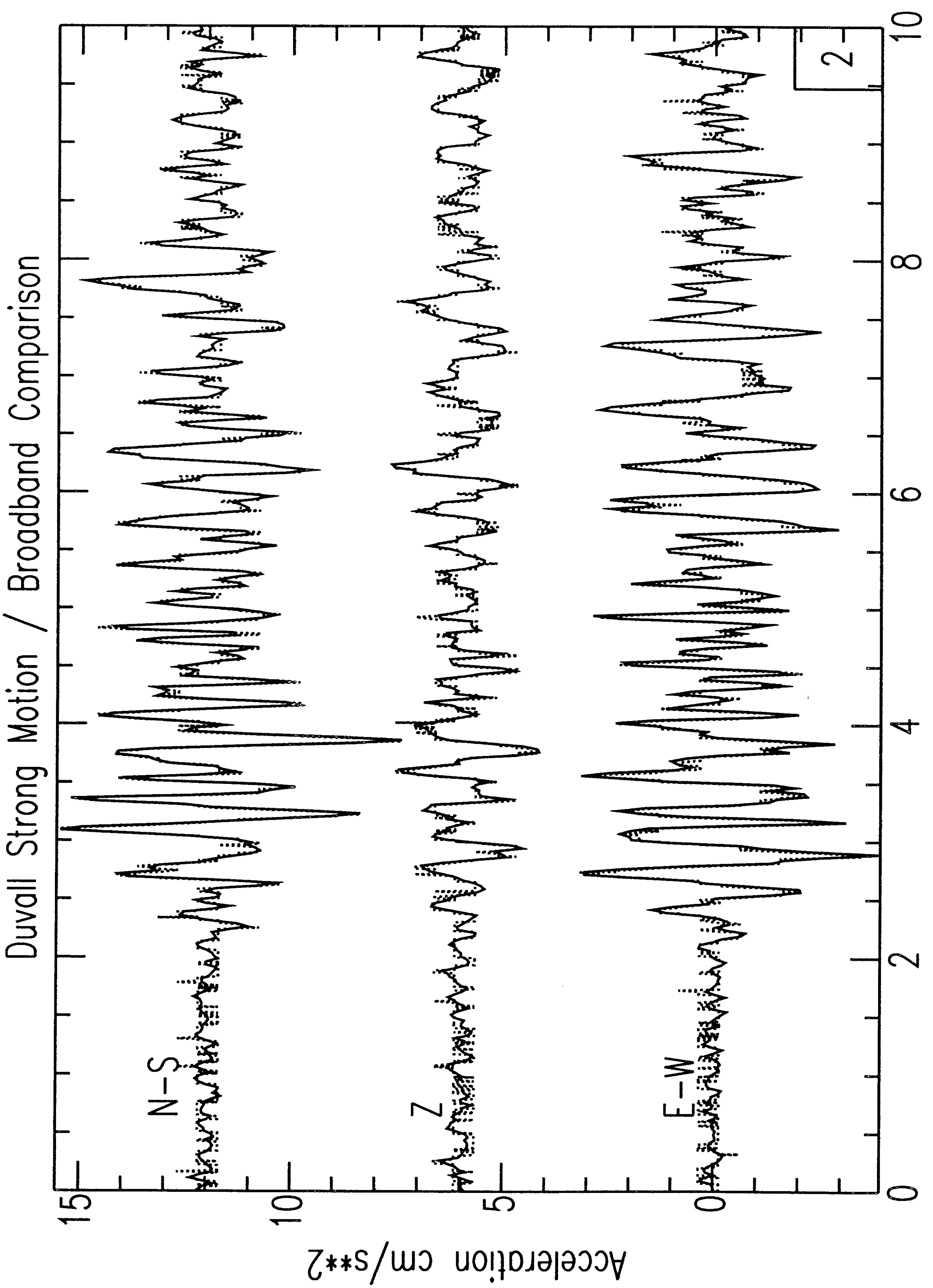
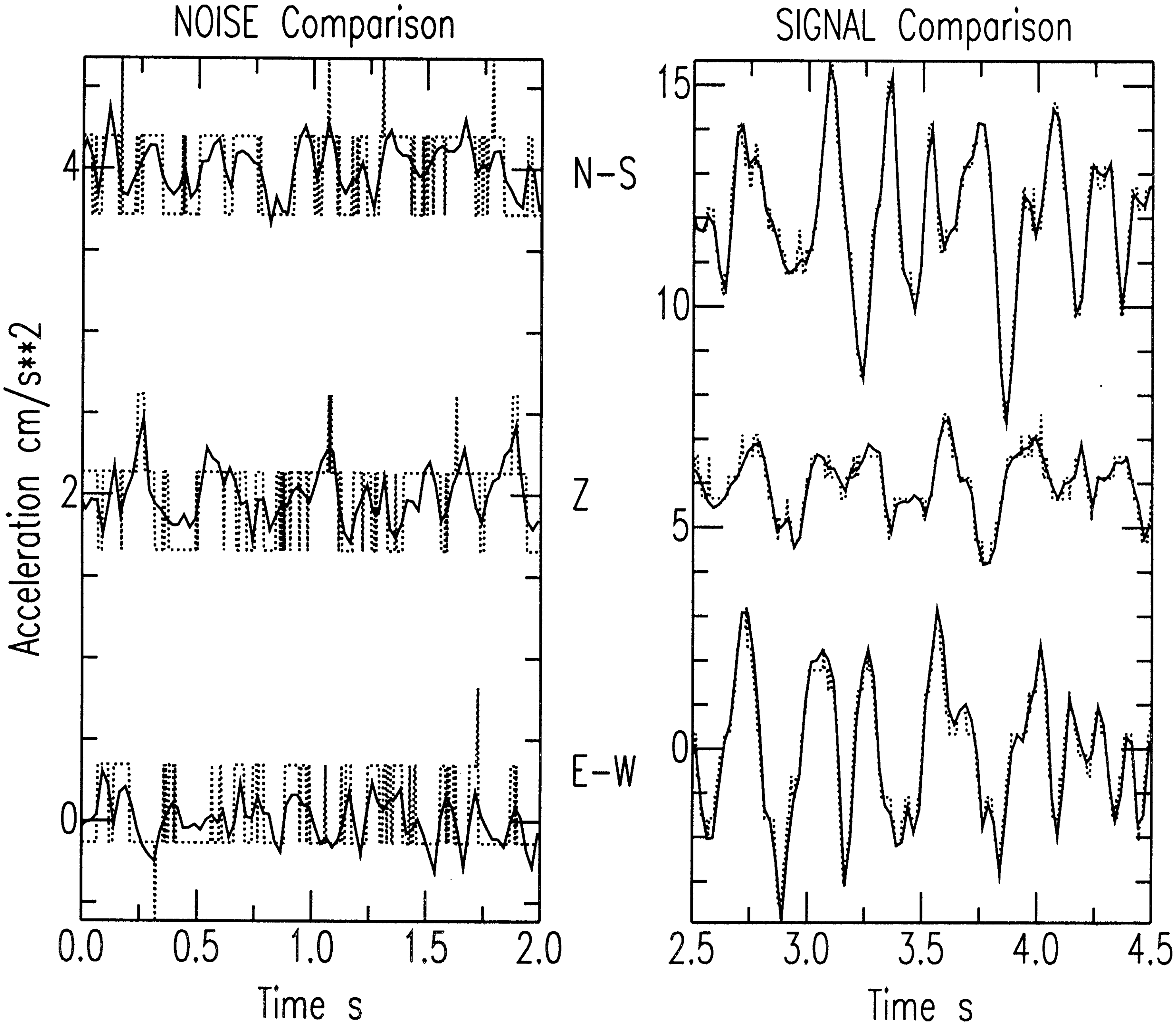

Duvall Strong Motion / Broadband Comparison
N-S
Z
E-W
2
Acceleration cm/s**2
0
5
10
15
Time s
0
2
4
6
8
10

Fig 2b


NOISE Comparison
SIGNAL Comparison
Acceleration cm/s**2
N-S
Z
E-W
4
2
0
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time s
Time s

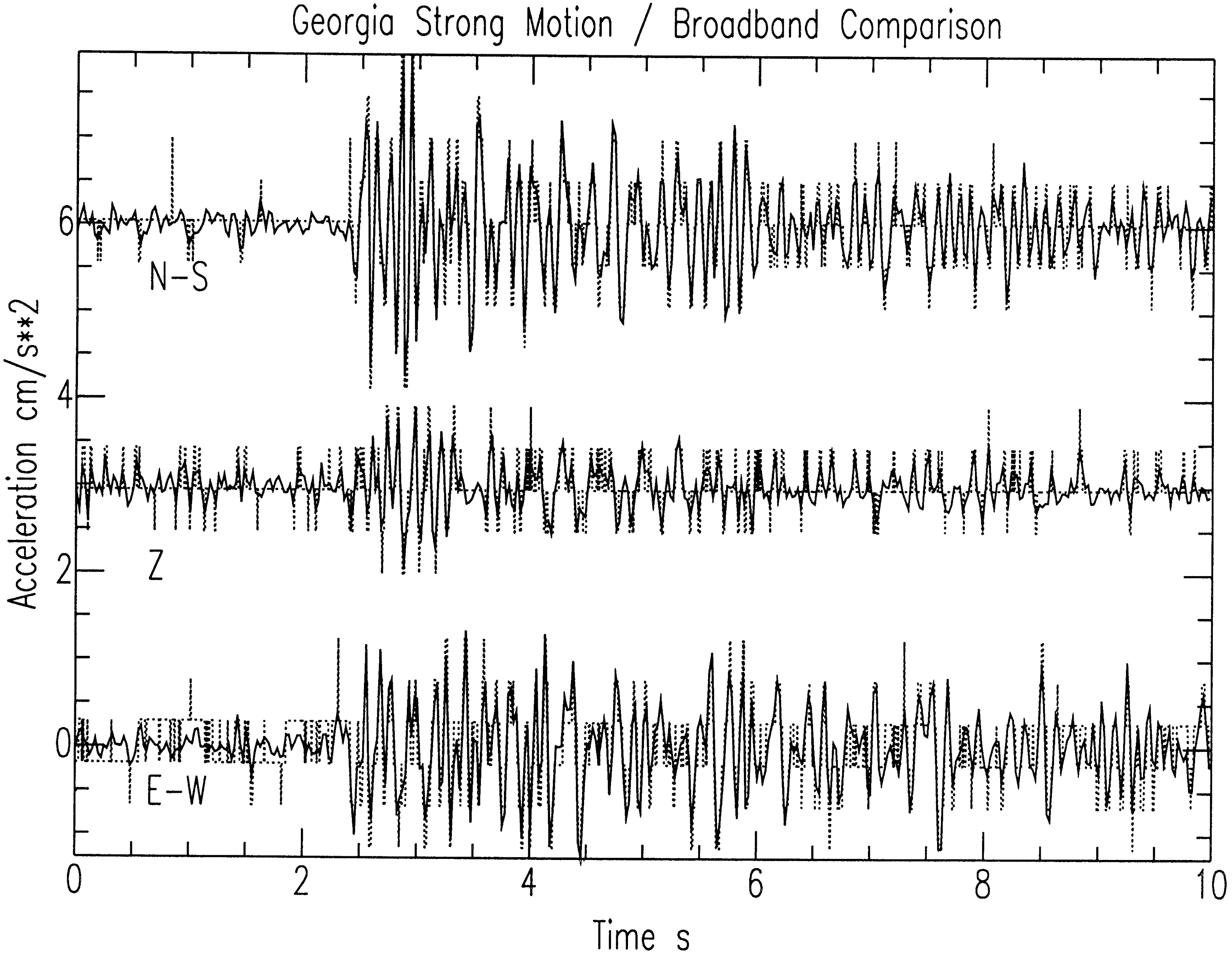
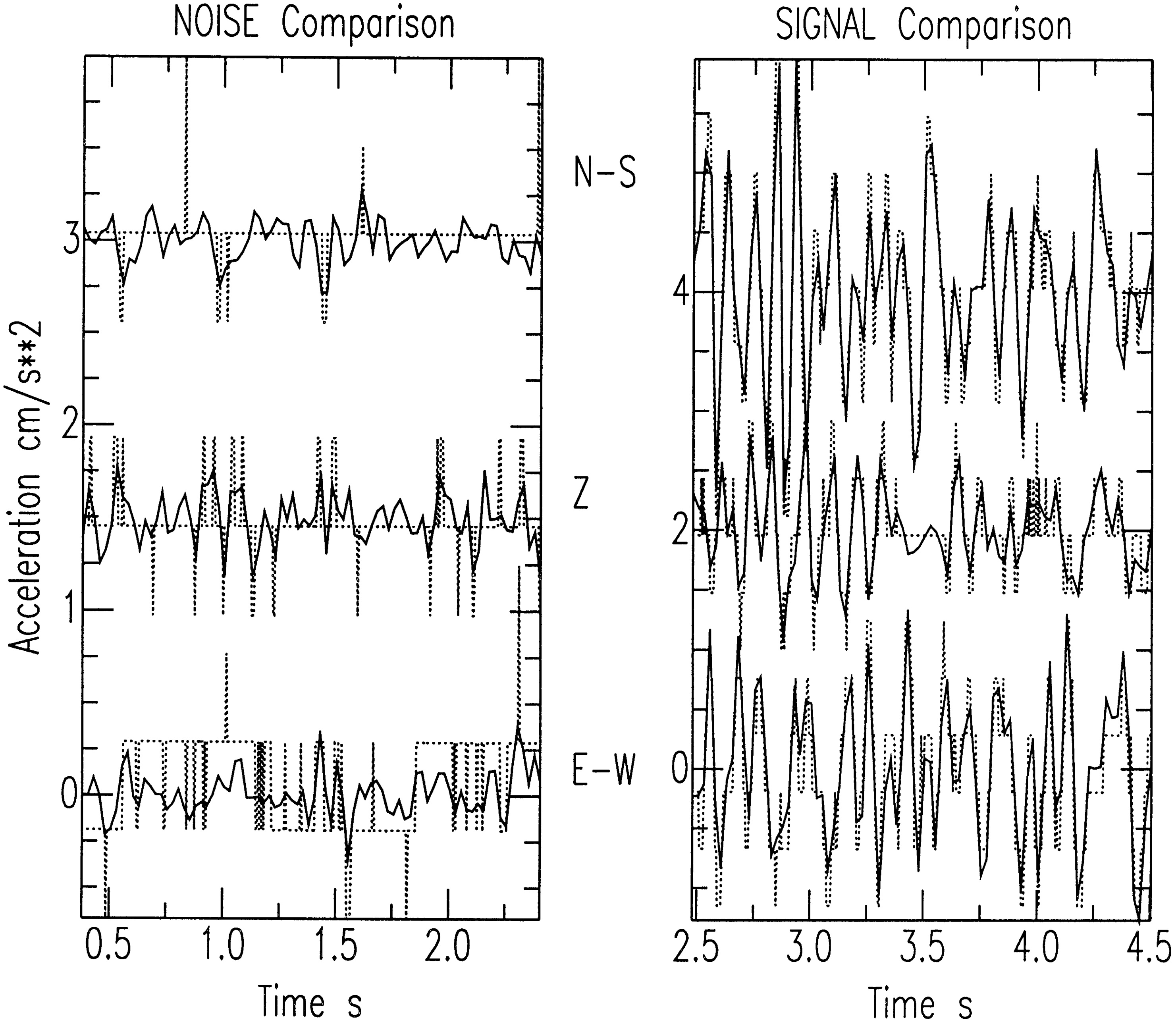

Georgia Strong Motion / Broadband Comparison
Acceleration cm/s**2
Time s
N-S
Z
E-W
0
2
4
6
0
2
4
6
8
10

Fig 3a


NOISE Comparison
SIGNAL Comparison
Acceleration cm/s**2
3
2
1
0
4
2
0
N-S
Z
E-W
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1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time s
Time s

Fig 3b

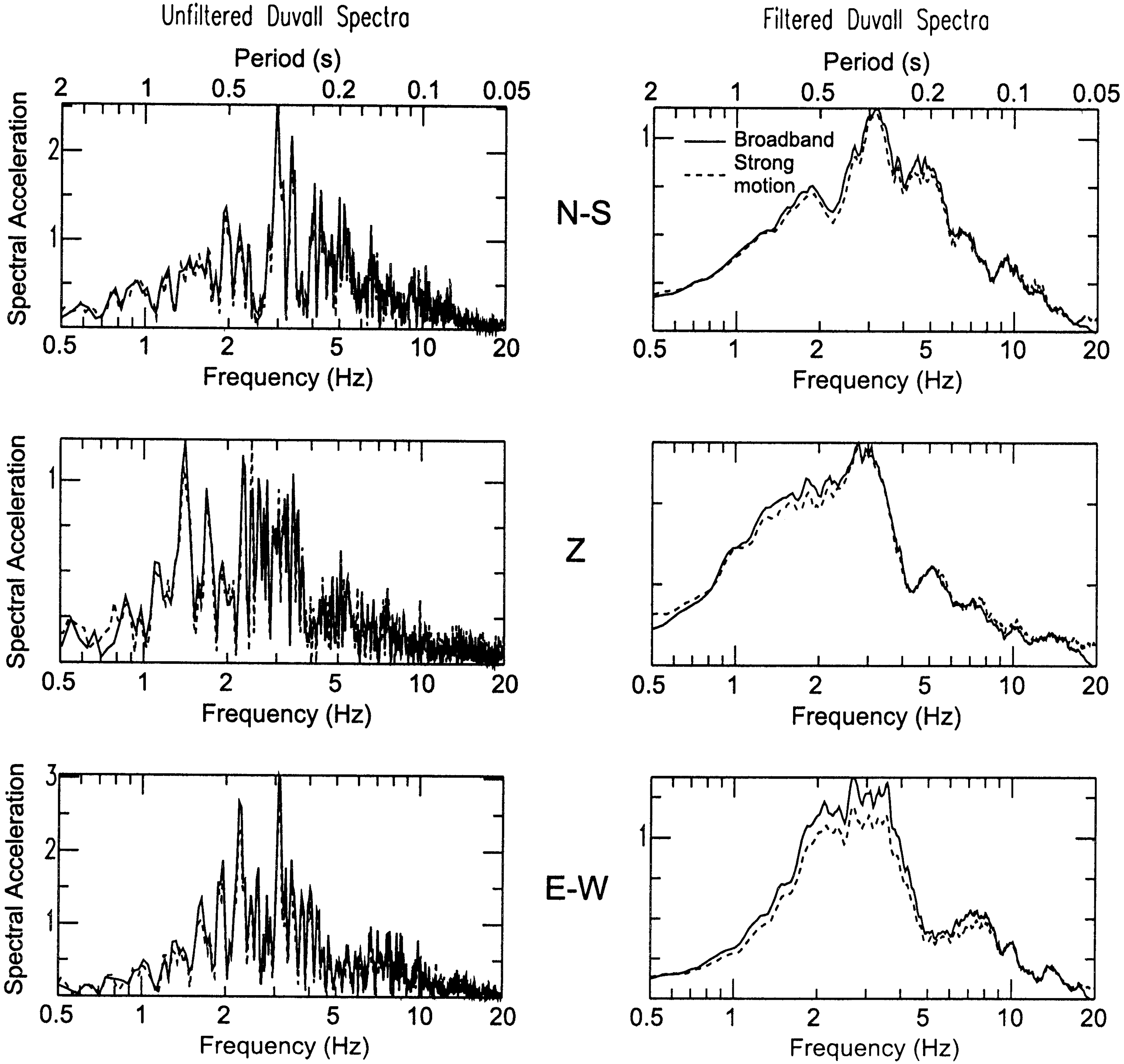

Unfiltered Duvall Spectra
Filtered Duvall Spectra
Period (s)
2
1
0.5
0.2
0.1
0.05
Spectral Acceleration
3
2
1
0.5
1
2
5
10
20
Frequency (Hz)
Broadband
Strong motion
N-S
Z
E-W

Fig 4

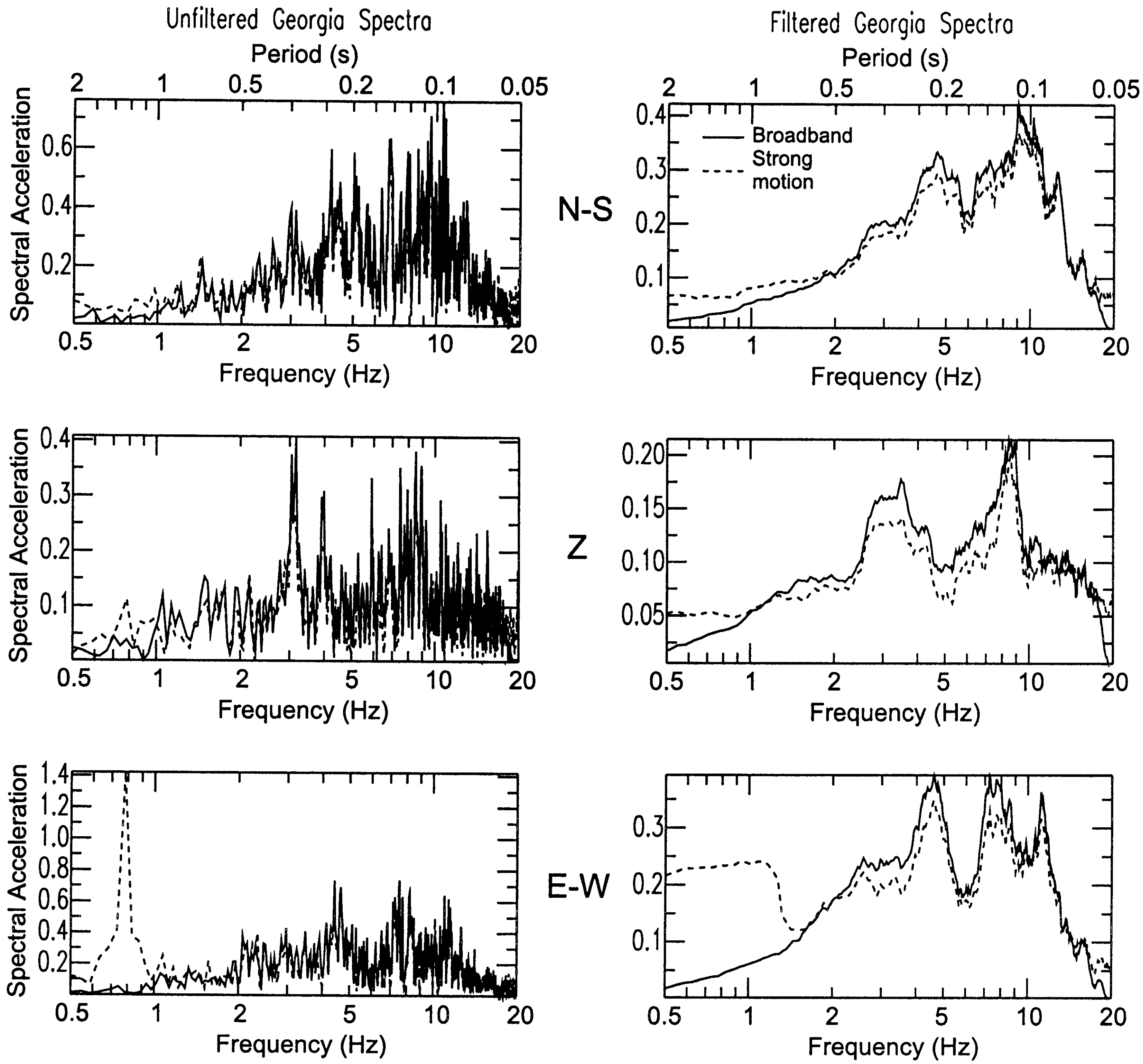

Unfiltered Georgia Spectra
Filtered Georgia Spectra
Period (s)
2
1
0.5
0.2
0.1
0.05
Spectral Acceleration
Broadband
Strong motion
N-S
Z
E-W
Frequency (Hz)
0.5
1
2
5
10
20
0.2
0.4
0.6
0.1
0.3
0.4
0.05
0.10
0.15
0.20
0.8
1.0
1.2
1.4

Fig 5

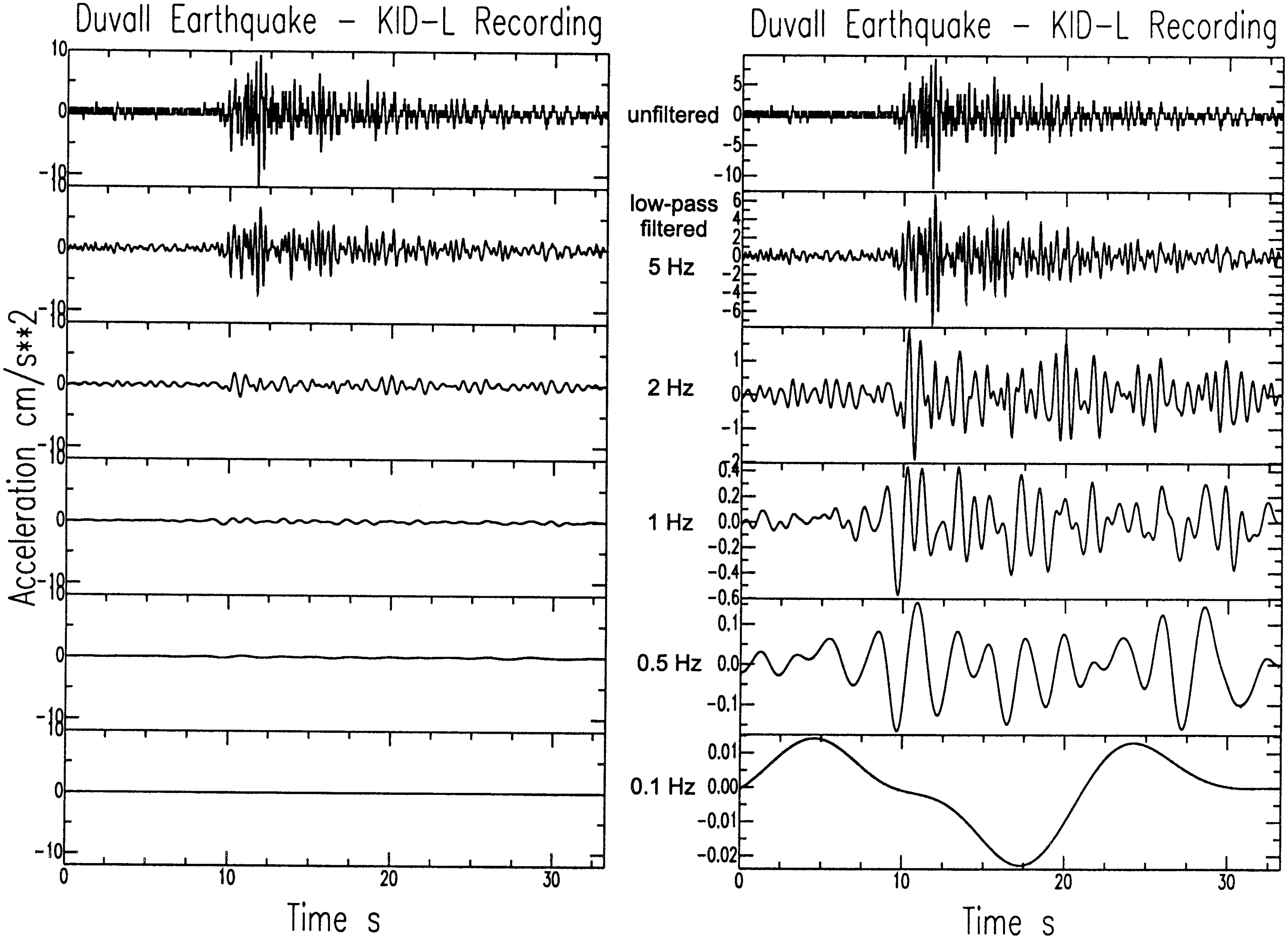
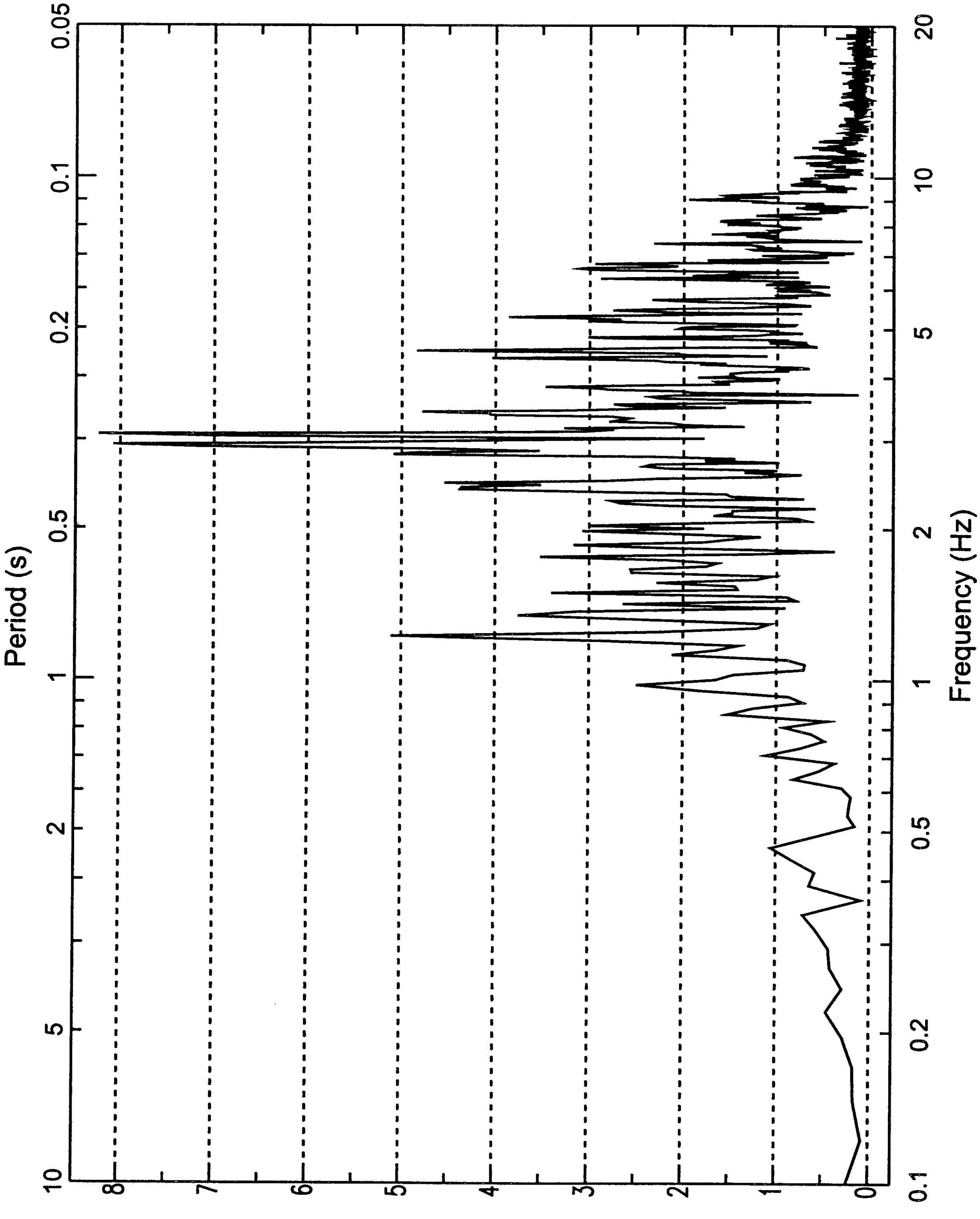

Duvall Earthquake - KID-L Recording
10
0
-10
Acceleration cm/s**2
0
10
20
30
Time s
Duvall Earthquake - KID-L Recording
unfiltered
5
0
-5
-10
low-pass filtered
5 Hz
6
4
2
0
-2
-4
-6
2 Hz
1
0
-1
1 Hz
0.4
0.2
0.0
-0.2
-0.4
-0.6
0.5 Hz
0.1
0.0
-0.1
0.1 Hz
0.01
0.00
-0.01
-0.02
0
10
20
30
Time s

Fig6

Fig 7

Fig. 7



Period (s)
10
5
2
1
0.5
0.2
0.1
0.05
Spectral Acceleration
0
1
2
3
4
5
6
7
8
Frequency (Hz)
0.1
0.2
0.5
1
2
5
10
20

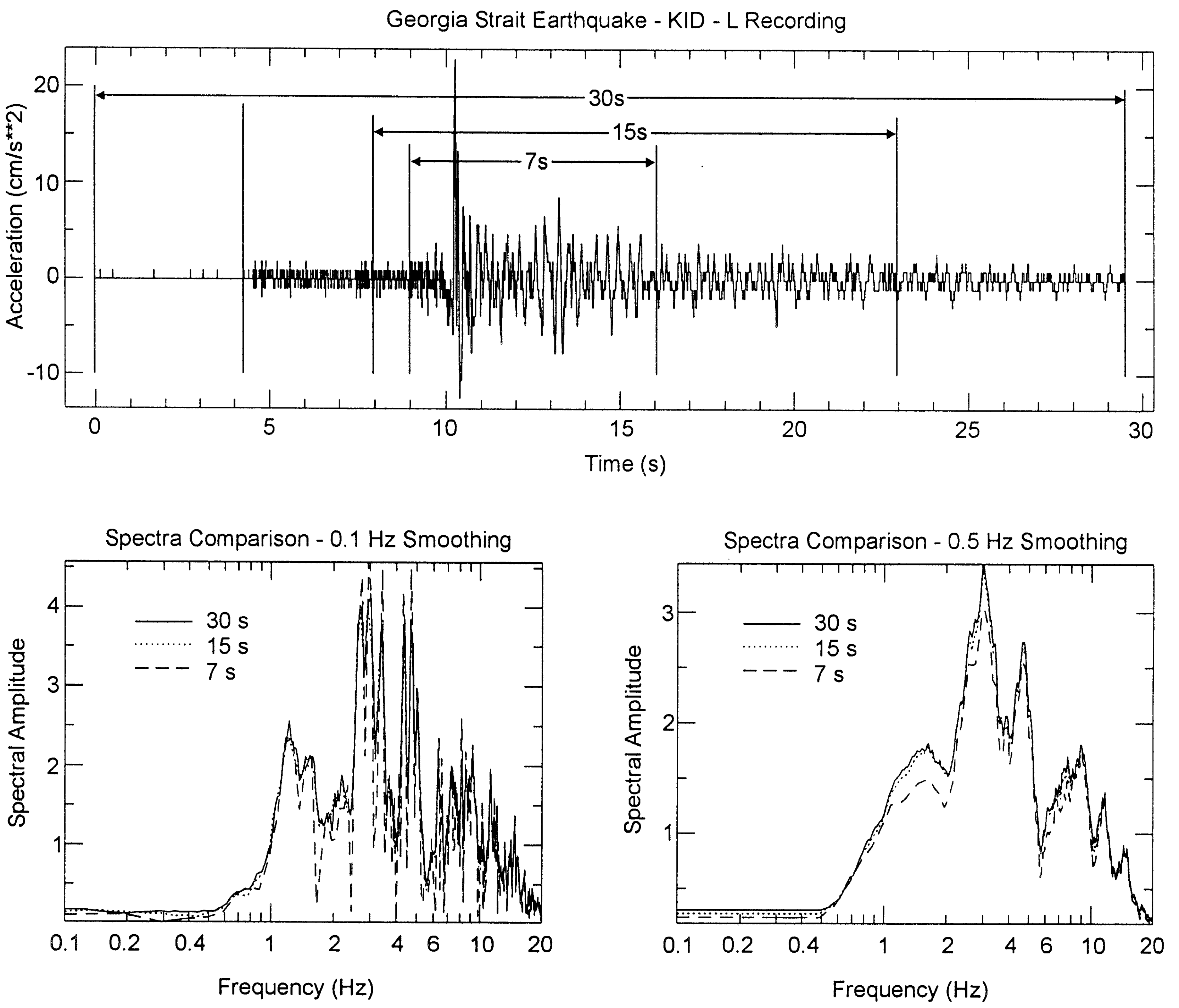

Georgia Strait Earthquake - KID - L Recording
Acceleration (cm/s**2)
20
10
0
-10
30s
15s
7s
0
5
10
15
20
25
30
Time (s)
Spectra Comparison - 0.1 Hz Smoothing
Spectral Amplitude
4
3
2
1
30 s
15 s
7 s
0.1
0.2
0.4
1
2
4
6
10
20
Frequency (Hz)
Spectra Comparison - 0.5 Hz Smoothing
Spectral Amplitude
3
2
1
30 s
15 s
7 s
0.1
0.2
0.4
1
2
4
6
10
20
Frequency (Hz)

Fig 8