# ACCELERATION, VELOCITY AND DISPLACEMENT NOISE ANALYSIS FOR THE CSMIP ACCELEROGRAM DIGITIZATION SYSTEM

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## SUMMARY

A series of tests were undertaken to establish the level and characteristics of processing noise associated with a scanning digitizer used by the California Strong-Motion Instrumentation Program (CSMIP). Digitizations of straight-line traces were used to determine the peak values of acceleration, velocity and displacement to be expected from intrinsic processing noise. The noise-level peak acceleration is about .0015 g, as expected from the digitizer step-size. This value is a constant and does not change with the cut-off period used in the long-period filtering. The peak velocity and displacement values increase as a function of increasing filter cut-off period. For 1-second period, peak velocity has approximately a 0.1 cm/sec uncertainty, and peak displacement has a 0.01 cm uncertainty. For a 5-second filter cut-off, these values increase to about 0.5 cm/sec and 0.5 cm, respectively. The velocity response (PSV) and Fourier (FS) spectra for straight-line digitizations increase linearly with period (decrease with frequency as $\omega^{-1}$), passing through approximately 1 cm/sec at 1 Hz (5% damping). Equivalently, the pseudo-acceleration (PSA) spectrum is approximately constant at a value of .003 g.

Digitization tests were also made using synthetic (tapered-sinusoid) accelerograms. These records were used to study the characteristics and noise levels of standard processing within selected frequency bands. These tests indicate that for certain accelerograms, the decimation (spectral folding) associated with the low-pass filtering can introduce spurious long-period energy into the data. Adequate filtering prior to decimation removes the effect, though it tends not to be severe for most earthquake accelerograms because of their spectral width. The correction can be achieved through a relatively minor modification of the original code. An additional minor modification can approximately correct the recently noted high-frequency inaccuracy of the standard instrument-correction algorithm.

## INTRODUCTION

Accelerograms recovered from an earthquake can provide much information about both the earthquake source and the ground shaking. The available information is increased through digitization and processing of the records. However, the interpretation of processed strong-motion data requires an adequate understanding of the level and character of the noise intermixed with the data. A full treatment of the noise present in processed strong-motion data requires separate analyses of the noise associated with

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digitization and the noise associated with the recording instrument. This study is limited to the analysis of the noise associated with accelerogram processing, by which is meant the sequence of digitization, integration and filtering. Total noise levels may be expected to exceed the levels discussed here; in any case, they are not less.

Several studies have treated the noise problems associated with a manual digitization process like that in use in the early 1970's at Caltech (Trifunac et al., 1973; Hanks, 1973; Berrill and Hanks, 1974). The introduction of automated digitization systems requires similar studies to establish the noise level associated with these systems. Trifunac and Lee (1979) have investigated processing noise characteristics for an automated digitization system at the University of Southern California. We here extend and update that analysis, including time-domain analysis, for the CSMIP facility, which is patterned after the Trifunac-Lee system. In these systems, the film accelerogram is scanned, while mounted on a rotating drum, by a travelling photodensitometer. A curve-follower algorithm constructs the digitized accelerogram from the resulting gray-level matrix. The acceleration record is then processed by the standard processing procedures.

## NOISE-LEVEL ANALYSIS

One method for investigating intrinsic system noise is to digitize straight-line, or fixed, traces on an accelerogram as though they were acceleration traces. Modern analog strong-motion recorders include two fixed traces (generated by mirrors affixed to the instrument chassis). Digitizing and processing these two straight lines, one treated as an acceleration trace and the other a fixed trace, yields a good estimate of the noise-floor of the processing system. The resultant output indicates the minimum levels of motion on an accelerogram discernable by the processing system.

The spectral results obtained from several records processed in this manner can be averaged to obtain a stable estimate of the shape of the noise spectrum. The average spectrum (PSV, 20% damping) shown in Fig. 1 was obtained by averaging the spectra from 8 accelerograms of 60 seconds length. For comparison, other noise-spectrum estimates from the literature are also shown in Fig. 1. The CSMIP noise spectrum is below that obtained by Trifunac and Lee (1979) but it is expected that, with recent improvements, their spectrum is close to the CSMIP spectrum.

Note that in Fig. 1, the manual-digitization noise spectrum (from Trifunac, 1977) is lower than the automatic-digitization spectra. However, as described in Trifunac et al. (1973) and Trifunac (1977), the spectral estimate for the manual digitization was obtained by digitizing a single straight line. That spectrum therefore is not strictly comparable, but is shown for reference.

Noise-floor curves such as that shown in Fig. 1 are very useful in interpreting processed strong-motion spectra. If any part of the strong-motion spectrum obtained during processing is low enough so that it approaches the noise spectrum, the indication is that any true signal, if present, is probably not recoverable from the noise.

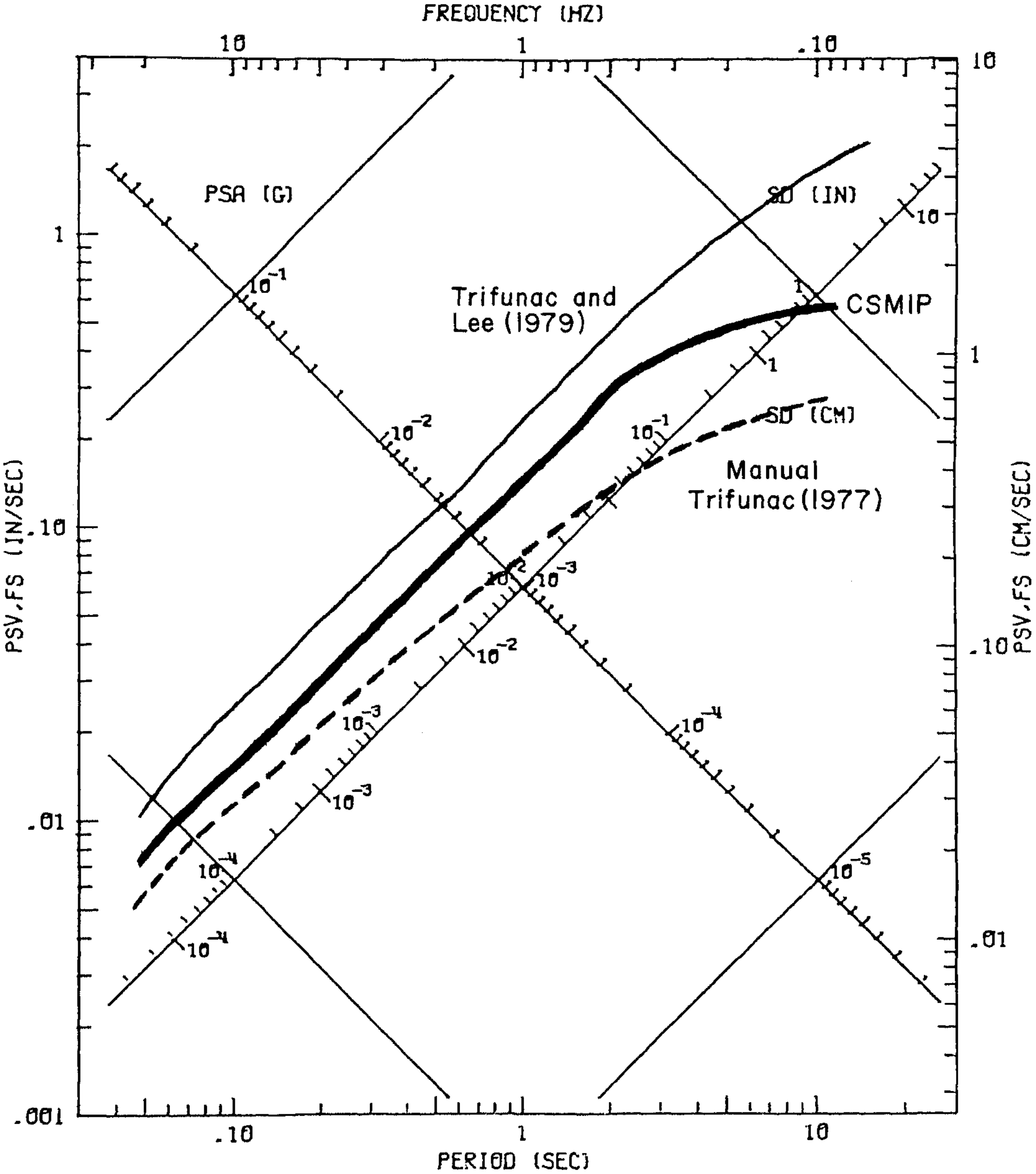

Figure 1. Noise-level spectra (PSV, 20% damping) for the CSMIP (heavy line) digitization system compared to other spectra from the literature. The CSMIP and the Trifunac and Lee (1979) spectra were obtained through dual fixed-trace digitizations (60 sec. records). The manual-digitization spectrum was obtained using a single straight line and is not strictly comparable, as discussed in the text.

It is quite informative to consider the levels and characteristics of processing noise in the time domain. Velocity and displacement records obtained for a straight-line digitization are shown in Fig. 2. These are the records obtained from the normal processing procedure, with the long-period filter cut-off set at 10 sec. period, 5 sec., and 2.5 sec., respectively. These records indicate, like the spectra in Fig. 1, that the longer-period parts of a processed record have more uncertainty. For example, an uncertainty of 1 cm is present in the displacement record if the data was processed with a filter cut-off of 10 secs. This uncertainty is reduced to about 0.04 cm if the data is processed with the cut-off set at 2.5 secs. Of course, all information above 2.5 secs. period is lost during this operation. A similar change in the uncertainty is observable in the velocity records, but the change is not as great. This comparison is clearer in Fig. 3, in which peak values of records like those in Fig. 2 are plotted against the associated cut-off period, for acceleration, velocity and displacement. Peak acceleration is independent of the cut-off period (for these periods). As integration of the flat acceleration spectrum would indicate, peak velocity increases linearly with period, and peak displacement increases as the square of period. These curves indicate the uncertainty in processed records for the full range of long-period filter cut-offs typically used. These three curves graphically show the limits of the system: any information below or to the right of these lines must be considered irrecoverable by the system.

For all digitization schemes, manual or automatic, the noise floor is related to the digitization step-size. Decreasing step-size decreases the noise floor until the limit of the dynamic range intrinsic to the recording medium is reached. On a practical basis, the decreasing step-size places increasingly severe hardware and/or software demands on a digitization system. Figs. 1 - 3 reflect the present noise levels of the CSMIP digitization system. It is projected that these can be lowered by a factor of two or more in the near future.

## FREQUENCY-SPECIFIC ASPECTS

Other approaches, in addition to straight-line digitizations, can be used to investigate processing algorithms. One method of verifying the frequecy response is to introduce a known signal as input and compare the output to the calculable result of the integration and filtering procedures. Tests of this type were performed in the course of system noise analyses by attaching a signal generator to a central recording accelerograph (CRA-1). The signal generator was used to generate a constant frequency sinusoid, with amplitude first increasing to a maximum and then decreasing (under manual control), as a test signal. This signal can be represented analytically as an exponentially damped sinusoid. Digitization of these artificial records was used to test and verify the processing at various frequencies. In the course of this work it was noted (Shakal, 1982) that the particular method of long-period filtering used in the standard Caltech procedures (Trifunac and Lee, 1973) can cause spurious long period results for certain input frequencies. Energy in the accelerogram near 5 Hz and its multiples is erroneously introduced (through the aliasing associated with decimation) at long periods (6 to 10 seconds and greater). Adequate filtering prior to decimation (with an Ormsby filter, for example), instead of simply applying the running-mean operator, removes the problem. The problem is seldom severe with earthquake records, however, since they usually have a spectrum much

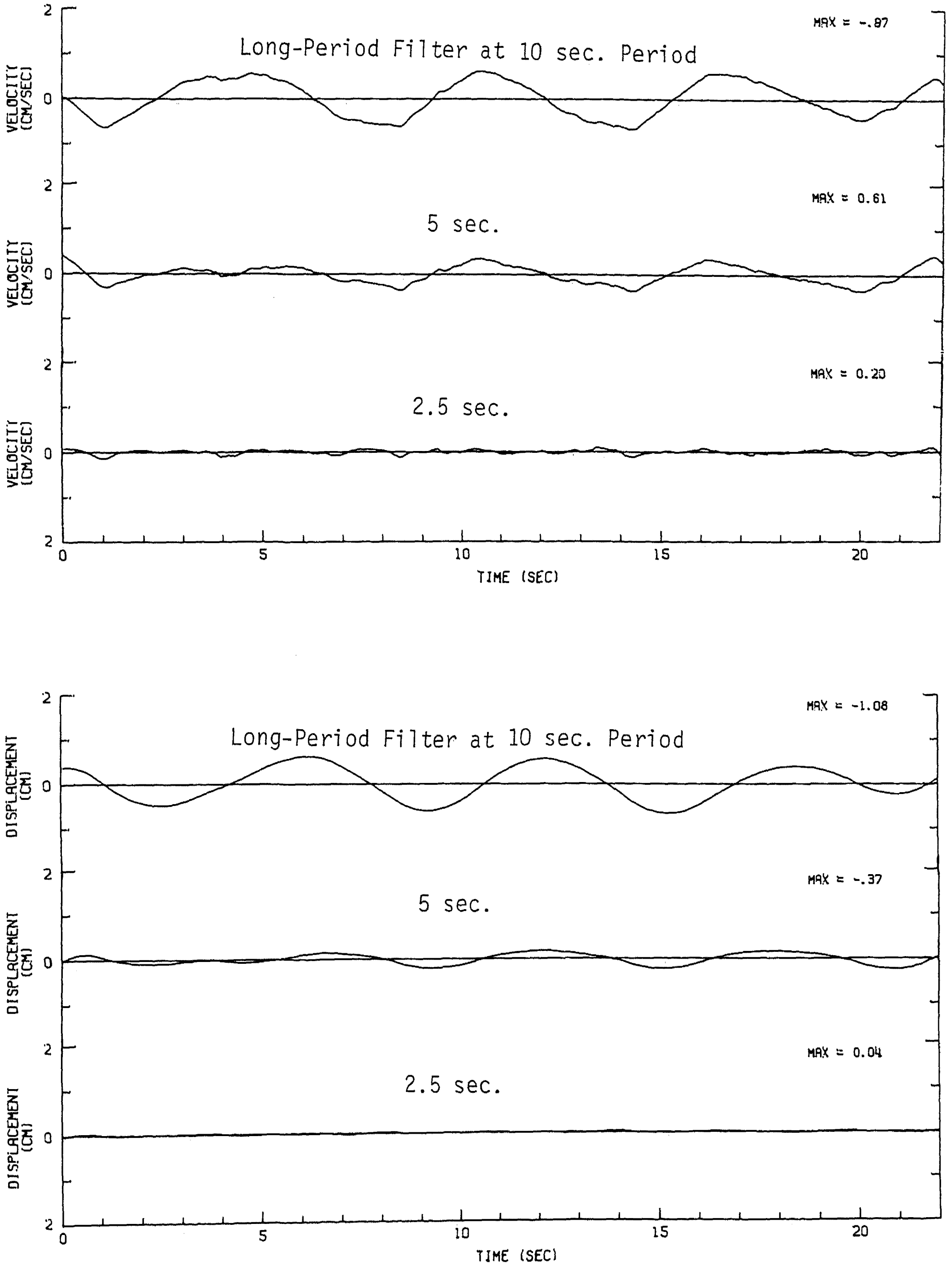

Figure 2. Noise-level velocity (upper) and displacement (lower) records obtained through straight-line digitization, with the cut-off period of the long-period filter varying from 10 secs. (upper) to 2.5 secs. (lower). These records show noise amplitudes present in a typical record processed with these long period filters.

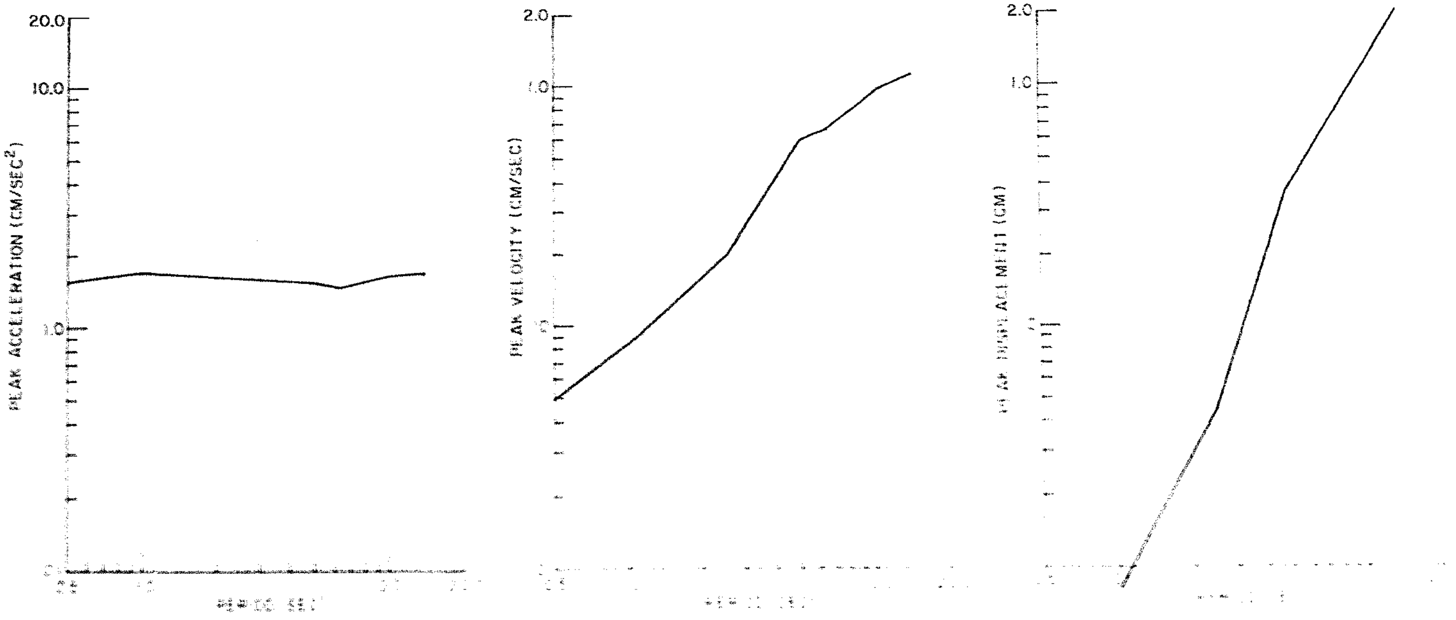

Figure 3. Processing noise present in a typical acceleration (left), velocity (middle) and displacement (right) record processed with a long-period filter cut-off period ranging from 0.5 sec to 15 secs.

wider than that of the tapered-sinusoid used in these tests. In any case a relatively minor modification to the standard code can be made which alleviates the aliasing. This modification is illustrated in the Appendix.

A second problem which has been noted to exist in the standard processing code can also be corrected with a relatively minor modification. Raugh (1981) and Shyam Sunder and Connor (1982) have noted that the standard instrument-correction algorithm inadequately corrects for the instrument response at high frequencies (15-25 hz). The problem is that the bridging-formula approximating the derivative has an increasingly large error at frequencies approaching the Nyquist frequency (half the sampling frequency). This suggests the simple expedient of performing the instrument-correction process using that same simple algorithm but applying it prior to desampling of the data from 100 down to 50 points/sec. This shifts the inaccuracy of the bridging operator to frequencies higher than the final 25 Hz Nyquist frequency. This entails only a minor modification of the original code, as indicated in the Appendix. Note that both this and the modification discussed above are very easy to make, though they may increase computing time by a few percent.

## ACKNOWLEDGEMENTS

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# APPENDIX

## USEFUL MODIFICATIONS TO STANDARD PROCESSING CODE

### Modification 1: Alleviate Spurious Long-Period Folded Energy

In subroutine BAS (p. 104 of Trifunac and Lee, 1973), replace lines BAS 122 through BAS 143 with the following:

```
C      CALCULATE WEIGHTS FOR PRE-DECIMATION FILTERING VIA ORMSBY    BAS 122
C      FILTER WITH FC=1.5 HZ, FN=3.0 HZ, INSTEAD OF RUNNING MEAN.   BAS 123
       ALR = 1.5*DDT                                                BAS 124
       NN = 1./ALR                                                  BAS 125
       ALC = 1.5*DDT                                                BAS 126
   (Copy and insert lines BAS 159 through BAS 172, with label
   '21' in lines BAS 164 and BAS 171 changed to '221', here.)
       DO 222 I=1,NN                                                BAS 141
   222 Q(I,1) = Q(I,1)*SUM                                          BAS 142
C      STEP #6  LOW-PASS WITH ORMSBY WEIGHTS, VIA SUBROUTINE SMU.   BAS 143
```

### Modification 2: Improve Accuracy of Instrument-Correction at High Frequency

In subroutine ICR (p. 96 of Trifunac and Lee, 1973), make insertions after lines ICR 100 and ICR 122. After line ICR 100 insert the lines:

```
C      NOTE: LOWPASS FILTER BUT DON'T DECIMATE TO 50 PTS/SEC.       ICR 100B
       NSKIP = 1                                                    ICR 100C
```

After line ICR 122, insert

```
C      HAVE CORRECTED FOR INSTRUMENT, NOW DECIMATE TO 50 PTS/SEC.   ICR 122B
       NSKIP = 2                                                    ICR 122C
```

and copy and insert, from subroutine SMU (p. 118), lines SMU 96 through SMU 106 here to do the decimation by two.