# STRONG MOTION DATA PROCESSING AND RECORDING AT UNIVERSITY OF SOUTHERN CALIFORNIA

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## ABSTRACT

A brief review is presented of the Los Angeles and Vicinity Strong Motion Network operated by the University of Southern California (USC), consisting of 80 stations deployed in 1978-1980, and of software developed and used at USC for digitization of accelerograms recorded on film, and for routine and specialized data processing of digitized or digitally recorded accelerograms. The currently used digitization system consists of a flatbed scanner, a PC, and the *LeAuto* software. The films are scanned at 600 dpi optical resolution, which is less than the limit of the hardware, but was found to be optimal, considering the limitations of the recorders, and benefit versus cost. The standard data processing methods used for further processing are a new generation of the software developed by Trifunac and Lee [1,2]. Baseline correction is performed by high-pass filtering, with cut-off determined for each component separately using a standard noise spectrum so that the recorded signal-to-noise ratio is greater than unity. The high frequency noise is removed by low pass filtering (with ramp 25-27 Hz for film records). In a batch mode of processing, the low frequency cut-off is determined automatically by the program, and is later verified by an operator, who can specify the filter manually if necessary. Filtering is performed in the time domain by Ormsby filter (a non-causal filter that does not introduce phase distortion), after appropriate even extension of the record. Digitally recorded accelerograms are also baseline corrected by high pass filtering, as random piecewise baseline offsets are not uncommon in digital accelerograms, even for small accelerations, and permanent displacements cannot be computed reliably from recorded three components of acceleration alone.

## INTRODUCTION

This paper reviews briefly the developments in strong earthquake motion recording and data processing at the University of Southern California (USC), carried out at the Strong Motion Recording and Data Processing Laboratories of the Civil and Environmental Engineering Department. The university is located in the heart of the Los Angeles metropolitan area, which in 1994 experienced the Northridge earthquake—a moderate size event ($M_L$=6.4), which occurred right beneath the densely populated San Fernando Valley, and has been so far the costliest natural disaster in the United States.

The Strong Motion Data Recording Laboratory was established in 1978 to serves the operation of the Los Angeles and Vicinity Strong Motion Network, which consists of 80 three-component accelerographs distributed throughout the metropolitan area (Anderson et al. [3]). This network, deployed in the period 1978−1980 with funding from the National Science Foundation, was the first urban strong motion network ever deployed worldwide, and during its 25 years of operation has recorded very valuable data of moderate and small local earthquakes, and of large distant earthquakes, the most damaging of which in the metropolitan area were the $M_L$=6.4 Northridge earthquake of January 17, 1994, and the $M_L$=5.9 Whittier-Narrows earthquake of October 1, 1987.

The Strong Motion Data Processing Laboratory was established in 1976 by Prof. M.D. Trifunac in support of the following research activities: (1) software development for routine and specialized processing of analogue and digital strong motion accelerograms, (2) routine processing of large accelerogram data sets and database organization for use in regression analyses, and (3) large scale regression analyses for empirical scaling of strong ground motion. Its activities were later extended to include also: (4) advanced calibration of strong motion instruments, (5) ambient vibration surveys of full-scale structures, and (6) structural health monitoring and damage detection. The hardware and software systems developed by the associated faulty, staff and graduate students include:

- System for automatic digitization of accelerograms recorded on film using flat-bed scanners and PC computers, driven by software package *LeAuto* developed by Lee and Trifunac [4]. This system replaced the older system, which ran on a Data General NOVA computer and used OPRONICS rotating drum scanner (Trifunac and Lee [2]).
- Software package *LeBatch* for routine uniform processing of digitized and digital strong motion accelerograms. It consists of three programs (Volume 1, 2 and 3) that perform baseline and instrument correction, filtering of high-frequency noise, computation of velocity and displacement by integration of corrected accelerations, and computation of Fourier and Response spectra (Lee and Trifunac [4]).
- System for field calibration of SMA-1 accelerographs, consisting of a tilt table and software package *Tilt* for routine processing of field calibration records, which solves an inverse problem to determine the transducer angular sensitivity constants and misalignment angles (Todorovska et al. [5,6], Todorovska [7]).
- Software for correction of accelerograms recorded on film for transducer misalignment and cross-axis sensitivity (Todorovska et al. [5]), implemented as a module of *LeBatch*.
- Software for instrument correction of coupled transducer-galvanometer recording systems (Novikova and Trifunac [8]), implemented as a module of *LeBatch*.
- Software for higher order instrument correction of force-balanced accelerometers (Novikova and Trifunac [9]), implemented as a module of *LeBatch*.
- System for ambient vibration testing of structures and soils, with PC based data acquisition and software for data analysis.

This paper summarizes the processed data recorded by the Los Angeles and Vicinity Strong Motion Network, and describe in more detail the *LeAuto* and *LeBatch* software systems, for automatic digitization of accelerograms recorded on film, and for further processing of digitized and digital strong motion accelerograms. More detailed information about this network, strong motion data sets released, and technical publications on data processing and use of strong motion data can be found on the Strong Motion Research Group web site at

www.usc.edu/dept/civil_eng/Earthquake_eng/

## LOS ANGELES AND VICINITY STRONG MOTION NETWORK

The Los Angeles and Vicinity Strong Motion Network consists of 80 stations, each recording three components of ground acceleration in “free-field” conditions (see Fig. 1; the stations are identified by their station number). The recording instruments are stand-alone SMA-1

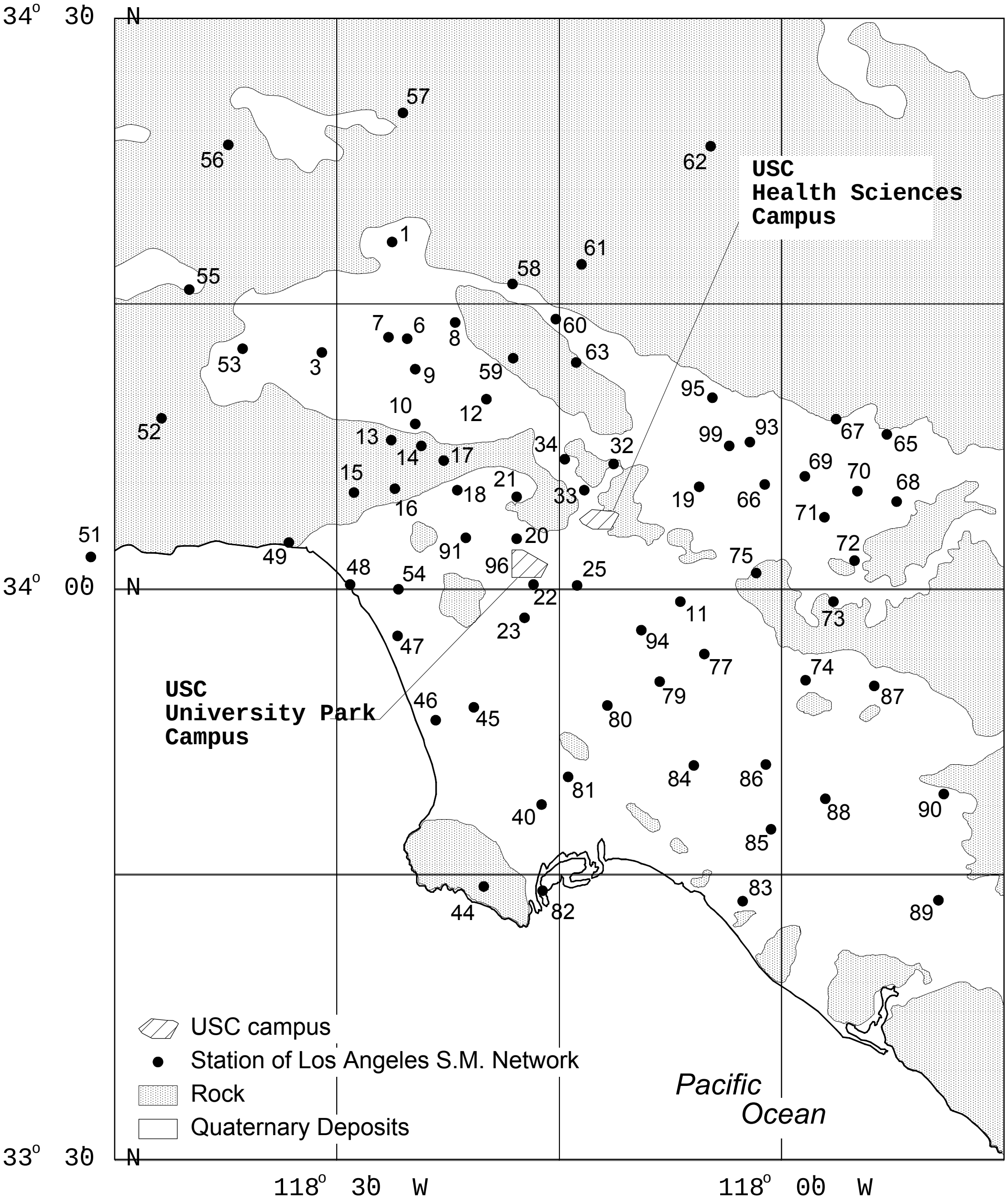


Figure 1: Los Angeles and Vicinity Strong Motion Network.

accelerographs, with absolute time. The array was planned and installed between 1978 and 1980 with financial support from the National Science Foundation, and became fully operational in the spring of 1980. This array was the first urban strong motion array. The purpose of the array has been to record strong ground motion in the metropolitan area, for use in studies on understanding and quantification of the spatial distribution of strong shaking, the attenuation of strong motion amplitudes with distance, the effects of the geological structure and local soils on the strong motion amplitudes, and the relationship between strong ground shaking and damage to structures. The Strong Motion Recording Laboratory at USC was established in 1978 to support the activities of the array.

During its 25 years of operation, the network has recorded many earthquakes. Table 1 shows a list of earthquakes for which data has been digitized and processed. These data are available free of charge from the USC Strong Motion Group web site, National Geophysical Data Center (NGDC) of NOAA (National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Boulder, Colorado), and COSMOS Virtual Data Center. Most significant have been the records of the $M_L$=6.4 Northridge earthquake of January 17, 1994, which was recorded by 65 stations, some of which were very close to the source (Todorovska et al. [10]). While the large number of stations that recorded a particular earthquake have been valuable for studying the spatial variability of ground motion, the multiple earthquake recordings at a particular station have been vary valuable for studies of the site effects at these stations. Shear wave velocity

**Table 1: Summary of processed data recorded by the Los Angeles Strong Motion Network**

| No. | Earthquake Name | Date and time (GMT) | M | H km | Number of records |
|---|---|---|---|---|---|
| 1 | Santa Barbara Island | 09/04/1981 15:50 | 5.5 | 5 | 7 |
| 2 | North Palm Springs | 07/08/1986 09:20 | 5.9 | 10 | 15 |
| 3 | Oceanside | 07/13/1986 13:47 | 5.3 | 9 | 6 |
| 4 | Whittier-Narrows | 10/01/1997 14:42 | 5.9 | 14 | 68 |
| 5 | Whittier-Narrows aft. (1) | 10/01/1997 14:43 | 3.8 | 15 | 16 |
| 6 | Whittier-Narrows aft. (2) | 10/01/1997 | | | 1 |
| 7 | Whittier-Narrows aft. (3) | 10/01/1997 14:45 | 4.4 | 14 | 33 |
| 8 | Whittier-Narrows aft. (4) | 10/01/1997 14:48 | 3.5 | 14 | 3 |
| 9 | Whittier-Narrows aft. (5) | 10/01/1997 14:49 | 3.9 | 13 | 41 |
| 10 | Whittier-Narrows aft. (6) | 10/01/1997 14:51 | 3.1 | 15 | 3 |
| 11 | Whittier-Narrows aft. (7) | 10/01/1997 15:12 | 4.0 | 15 | 35 |
| 12 | Whittier-Narrows aft. (8) | 10/01/1997 15:17 | 3.3 | 15 | 2 |
| 13 | Whittier-Narrows aft. (9) | 10/01/1997 15:59 | 3.8 | 15 | 12 |
| 14 | Whittier-Narrows aft. (10) | 10/01/1997 16:21 | 3.3 | 16 | 2 |
| 15 | Whittier-Narrows aft. (11) | 10/01/1997 19:11 | 3.4 | 15 | 1 |
| 16 | Whittier-Narrows aft. (12) | 10/04/1997 10:59 | 5.3 | 13 | 60 |
| 17 | Whittier-Narrows aft. (13) | 02/11/1998 15:25 | 4.7 | 17 | 37 |
| 18 | Sierra Madre | 06/28/1991 14:43 | 5.8 | 12 | 65 |
| 19 | Landers | 06/28/1992 11:57 | 7.5 | 5 | 61 |
| 20 | Big Bear | 06/28/1992 15:05 | 6.5 | 5 | 50 |
| 21 | Northridge | 01/17/1994 | 6.7 | 18 | 65 |
| 22 | Northridge aftershocks | 01/17/1994 to 03/23/1994 | >5 | | 115 |
| 23 | Hector Mine | 10/16/1999 | 7.1 | 6 | 39 |

profiles were measured at all stations in 1993, and were readily available at the time of the Northridge earthquake. All the stations were fully recalibrated in 1995, including sensitivity constants and transducer misalignment angles [Todorovska et al. [5,6]).

## DIGITIZATION OF ANALOG ACCELEROGRAMS AND DATA PROCESSING

This section presents a brief review of the developments in hardware and software for automatic digitization of accelerograms recorded on film, and of the software packages *LeAuto* and *LeBatch* for automatic digitization and for routine digital signal processing of accelerograms. This is followed by a discussion of issues in quality of digitization, and computation of permanent displacement from digital accelerograms.

### Developments in Hardware and Software

Optical scanners were first introduced in routine digitization of accelerograms in the late 1970s, and replaced the old hand digitization system (Trifunac and Lee [1]). The first such system, designed for the needs of the Strong Motion Data Processing Laboratory and described in Trifunac and Lee [2], used an OPTRONICS rotating drum scanner, driven by a Data General NOVA mini computer. This system was operated at resolution (of 50 x 50 microns (508 dpi), considered optimal for the particular application, even though its highest resolution was four times larger (12.5 x 12.5 microns or 2032 dpi). The cost of hardware of this system was $180,000 in 1977. About 10 years later, this expensive system was replaced by a much more affordable one that used a flatbed scanner, driven by a PC. The first such system ran on IBM PC AT and used HP ScanJet II Plus with 300 dpi optical resolution. This new system is described in Lee and Trifunac (1990). At present, a system with HP ScanJet 4c (600 dpi optical resolution), driven by a Pentium PC is used. The cost of hardware of this system is well under $5,000. This dramatic progress progress in hardware capabilities (scanner resolution, capacity of hard disk storage, CPU speed, typical scanning time, and typical operator time) and even more dramatic reduction of hardware cost is illustrated in Fig. 1, redrawn from Trifunac et al. [11].

### The *LeAuto* Software Package for Automatic Digitization of Film Records

Although digital accelerometers are replacing the analog ones, most of the significant strong motion data, at least in the United States, has been recorded on film, and it may take several decades until the newly deployed digital instruments record such significant data. There is still need for high quality digitization of analog records because there are analog strong motion instruments still deployed which may record in the future, and because of already recorded analog data that has not been digitized, or has been digitized inadequately.

The main steps in automatic digitization of accelerograms are:

(1) Analog to digital conversion of the film image into a binary or gray-scale digital bitmap. The gray level of each pixel describes the optical density of the film at that location.

(2) Estimation of the traces based on the bitmap by automatic trace following. The operator specifies the threshold gray level that separates the trace from the background, and minimum trace width in pixels.

(3) Interactive editing of the set of line segments created automatically in step 2.

(4) Trace concatenation, in case of long records that require several separately scanned pages, and saving the trace coordinates (in the scanner coordinate system) and other information (e.g., scanning resolution and trace type) into a disk file, in format suitable for further processing (involving instrument and baseline corrections, Trifunac [12,13]).

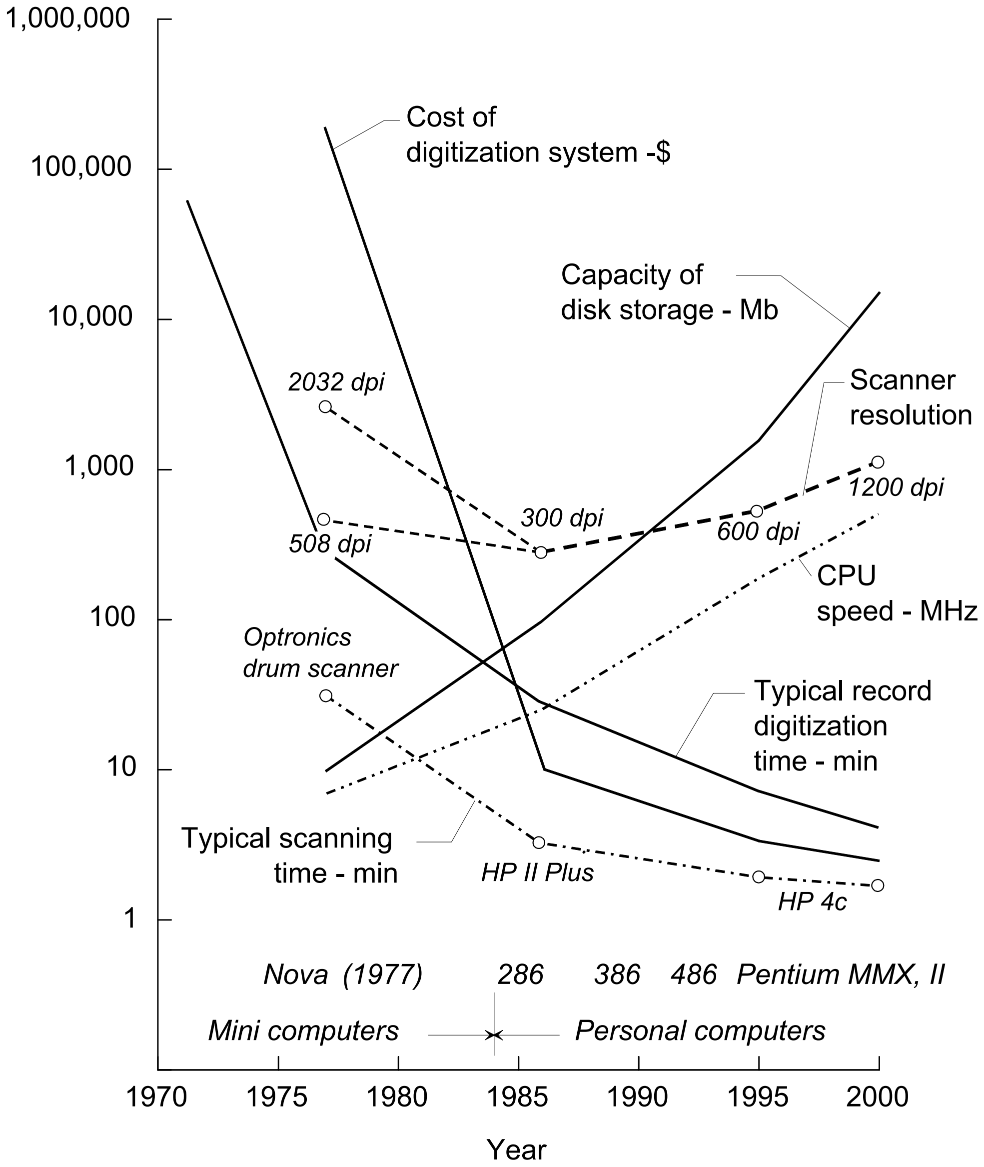


**Figure 2: Evolution in the hardware capabilities for automatic digitization of accelerograms, and reduction of cost and operator time**

These tasks are performed by four computer programs with respective generic names: *Film*, *Trace*, *TV* and *Scribe* (Trifunac and Lee [2]). These programs have evolved with the evolution of hardware. Numerous major changes and improvements have been added in the late 1980s (Lee and Trifunac [4]) and again in 1995/96, but the sequence of tasks has not changed. Our current software package, *LeAuto*, consists of programs *LeFilm*, *LeTrace*, *LeTV* and *LeScribe*. *LeFilm* is interactive, menu driven program which drives the scanner to produce a gray-scale bitmap image of the film record (256 levels of gray is the default mode; the other two modes are binary black-and-white and gray-scale at 16 levels of gray). The operator interactively chooses a minimum size rectangular window containing all the necessary information to be saved for further processing, and an optimum threshold level and minimum trace width for the automatic trace following by the next program. The operator also defines the starting points for each trace and trace type. Program *LeTrace* performs the trace following and is entirely automatic. Program *LeTV* is entirely interactive and menu driven. The trace editing is the most time consuming part of the procedure. The program efficiency and the quality of the output depend on the operator training and experience. The operator intervention consists of deletion of line segments resulting from imperfections of the film record (scratches and dirt particles), joining consecutive segments of a particular trace, adding and deleting points in a line segment, and also completely redigitizing selected portions of traces at a threshold level different from the one used by *LeTrace*. Most of the modifications of this program have aimed to help the operator make decisions and ease the editing process as much as possible. Added options include dynamic optimization of threshold levels, and monitoring the top or bottom edges of a trace—useful when an acceleration trace is touching a baseline. The last program, *LeScribe*, can be executed in an automatic or interactive mode. The former is used for short, one page, film records. The later is used for multiple page records and allows operator intervention and visual control of joining the trace segments from different pages.

## Some Issues in Quality of Automatic Digitization

In examining the quality of some commercially processed records of the 1994 Northridge earthquake, Trifunac et al. [11] pointed out to several issues, described in what follows

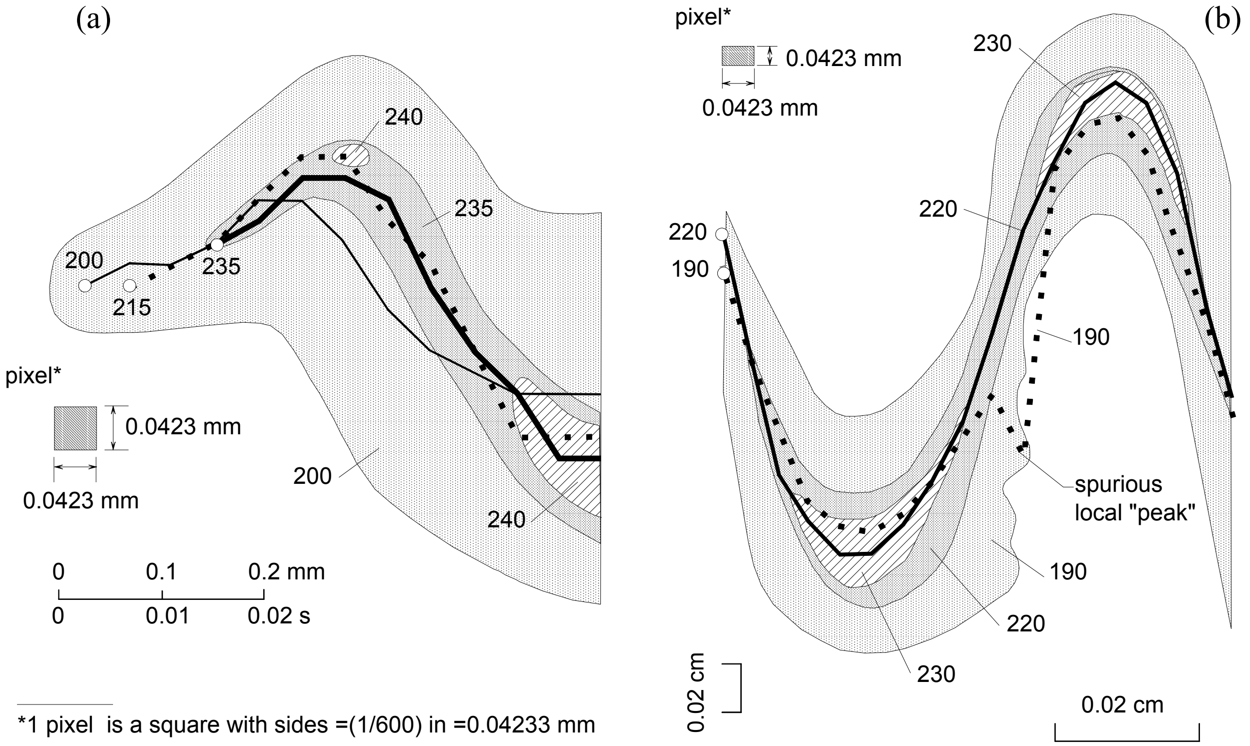
1. Synchronization of the acceleration traces, i.e. the choice of the position of the first digitized point. This is crucial for many applications, e.g. inversion of the earthquake source mechanism, computation of the radial and transfer components of motion and particle motion, analyses of wave propagation in buildings, and correction for cross-axis sensitivity and transducer misalignment (Todorovska [7] ). As illustrated in Fig. 3a, the beginnings of the traces are weak, and the position of the first point depends on the threshold level. The most recent version of *LeAuto* software has an option to choose the first point based on an objective criterion.

2. Non-uniform optical density of the traces, varying depending on the amplitude of motion, as well as randomly. The trace is, in general, lighter for larger trace amplitudes, but it is darker at the very peak. The position of the traces estimated by the program depends on the adopted threshold level. Too high threshold level leads to discontinuous traces, while too low threshold level may lead to artifacts such as spurious peaks. This is illustrated in Fig. 3b, which shows appearance of the scanned image and the outcome of automatic trace following

for different choices of threshold level, for 600 dpi scanning resolution with 256 level gray scale. A spurious peak is seen in the digitized data for lower threshold level (190). For higher threshold levels (e.g., 230), the trace image becomes discontinuous.

3. Smoothing of the high frequency peaks, caused by merging and partial overlapping of the trace just below the peak, due to finite thickness of the light beam exposing the film. This problem is pronounced for vertical acceleration traces, which usually contain more high frequencies than the horizontal accelerations, especially in the near-field of moderate and large earthquakes, resulting in rapidly oscillating traces with low optical density. They require lower than average threshold levels for automatic trace following, otherwise the trace is not continuous. On the other hand, lowering the threshold level smooth out the high frequency variations. This problem cannot be solved by reducing the pixel size. Its consequences can be diminished only by reducing the trace width on the film (by careful focusing), and by increasing the film speed beyond 1 cm/s.

4. Distortions due to high-contrast preprocessing of the film image. Moderate enhancement of contrast can be useful (and is sometimes essential), but it may also lead to complicated distortions of the traces that are not acceptable.



*1 pixel is a square with sides =(1/600) in =0.04233 mm

**Figure 3: (a) Illustration of a bitmap image of a trace beginning for different threshold levels (200, 215 and 235), and the corresponding outcomes of automatic digitization. (b) Appearance of the scanned image and the outcome of automatic trace following for different choices of threshold level (redrawn from Trifunac et al. [11]).**

5. Non-uniform film speed, including stalling. Non-uniform but continuous film speed is corrected for by digitizing the 2PPS signal, created electronically and hence believed to be more accurate than the speed of the motor driving the film, which is controlled mechanically. Some stalls are possible to correct for by inserting "gaps" into the scanned bitmap image, and recreating manually the missing portion of traces.

6. Rotation of the digitized traces, which occurs if the film is not well aligned with the scanner, and can be corrected for by adding a pair of fiducial marks and rotating the digitized traces.

The errors due to these problems can be either eliminated or significantly reduced, automatically by intelligent algorithms or manually by operator intervention. The most important factor determining the quality of the processed data is the experience of the operator and rigorous quality control of the outcome of the automatic trace following.

Scanning the image with a 256 level gray-scale is highly recommended, while digitization from a binary black-and-white bitmap image is discouraged. A major addition to the *LeAuto* software is a *self-learning algorithm with adaptive threshold level* for automatic trace following, implemented in the editing phase (*LeTV*) for applications within operator-defined windows.

There is a common misperception that the accuracy of estimating the high frequencies in a record will increase significantly by scanning the film record at a higher resolution. This is true only up to a limit. For example, the "smoothing" of the amplitudes of the sharp peaks can be eliminated only by better focusing of the light beam (possible only up to a certain degree) or by increasing the film speed. Our experience shows that, for higher scanning resolution (600 dpi), the digitized signal detects more noise (high frequency errors) due to imperfections on the film, such as scratches and dust (these imperfections are "not seen" or are "smoothed out" by larger pixels, for lower scanning resolutions e.g. 300 dpi).

### The *LeBatch* Software Package for Routine Processing of Digitized Accelerograms

The output of the digitization phase consists of coordinates of the digitized traces, which include acceleration traces, fixed traces, the 2 pulse per second (2PPS) trace, and the absolute time trace, if there is no 2PPS trace, all in the scanner coordinate system and units. The further processing is performed by the *LeBatch* software system, which consists of programs *Volume1*, *Volume2* and *Volume3*—further developments of the software developed by Trifunac and Lee [1,2].

Program *Volume1* reads the digitization output file, and for each acceleration trace, subtracts the nearest baseline, scales the trace coordinates in units of time (using the 2PPS trace if available, or nominal film speed, which is 1 cm/s for most SMA-1 accelerographs) and acceleration (using the sensitivity constant for the respective transducer, which can be supplied interactively or in a file), and removes the linear trend. These data, referred to as "uncorrected" acceleration, is unequally spaced, and is saved in a file.

Program *Volume2* reads the *Volume1* output file, performs "instrument correction" and band-pass filtering to insure recorded signal to noise ratio grater than unity, and integrates the corrected acceleration twice to obtain velocity and displacement. More rigorous filtering, if necessary for a particular application, can be done later by the user. *Instrument correction* refers to correction for the fact that the trace represents the transducer response, rather than the input shaking itself, and represents de-convolution of the input motion and the system function, which is performed in the time domain (Trifunac [12]). This process requires knowledge of the system function, i.e. transducer transfer-function, which in practice reduces to knowledge of the instrument constants for an adopted transducer response model. Program *Volume2* has a built in capability to correct for transducer misalignment and cross-axis sensitivity (Todorovska et al. [5]; Todorovska [7]), for coupled transducer-galvanometer systems, and to do higher order corrections for force-balanced accelerometers (Novikova and Trifunac [8,9]), but these routines require additional constants (besides transducer linear sensitivity, natural frequency, and damping ratio), which are measured by detailed calibration. The highest frequency that can be estimated reliably from a film record is limited by the scanner resolution and finite width of the light beam that "impresses" a trace on the film.

The highest frequency that is left in the record also depends on the sampling rate of the final output of *Volume2*, which is currently set to 100 points per second, which implies Nyquist frequency of 50 Hz (it is noted here that all of the operations within *Volume2* are performed at a higher sampling rate). The smallest frequency is also limited by the hardware, but in a different way. Film records have a wavy baseline, which is removed by high-pass filtering, as first proposed by Trifunac [13], also called *baseline correction*. The low frequency cut-off is determined so that the recorded signal to noise ratio is grater than unity in the pass band, with respect to a representative noise spectrum for the hardware used, which increases with increasing period (i.e. with decreasing frequency). In standard *Volume2* processing, the low frequency cut-off is determined automatically by the program, and is verified later by an operator, while the high frequency cut-off is fixed at 25-27 Hz. Filtering is performed in the time domain (i.e. using convolution) by Ormsby filters (a box function in the frequency domain, tapered by a linear ramp function), after appropriate even extension of the record. This simple filter is non-causal, but does not cause phase distortions Lee and Trifunac [14]. The even extension of the record eliminates jumps in the time series at the beginning and end, hence reducing the Gibbs effect, by adding redundant information outside the domain of the data rather than by removing information from the domain of the data, which happens in the case of tapering—the common solution to reduce Gibbs effects.

*Volume3* program computes spectra for each acceleration trace (Fourier transform amplitude of acceleration, and response spectra amplitudes for five damping ratios—spectral acceleration, spectral velocity, spectral displacement and pseudo spectral velocity). Detailed description of the *LeBatch* software can be found in Lee and Trifunac [4].

### Processing of Accelerograms Recorded Digitally

Accelerograms recorded by force balance accelerometers and digital recorders are also routinely baseline corrected—by high pass filtering—despite their high dynamic range and low threshold of recording (the resolution of recording at present approaches 135 dB; Trifunac and Todorovska [15]). The first reason is long period noise of the instrument, such as random piecewise baseline offsets, which are not uncommon in digital accelerograms even for small accelerations (Shakal et al. [16], presented at this workshop). The second reason is long period "noise" from the physical limitation of the transducer to record “pure” translations, mostly due to contributions to the recorded motions from tilting and torsion, as well as from cross-axis sensitivity and transducer misalignment. Trifunac and Todorovska [15] used artificially generated rocking and torsional ground motion time histories and more complete equations of transducer motion to illustrate the contributions from ground tilting and torsion to the recorded motions, which showed that, for smaller frequencies, these contributions become larger than the threshold level of recording. They concluded that, to correct for these contributions, and hence be able to compute *reliably* permanent ground displacement, it is necessary to record *all six* components of ground motion (three translations and three rotations). The same was stated earlier by Graizer [17], and is also addressed in detail in Graizer [18] (presented at this workshop).

## DISCUSSION AND CONCLUSIONS

The digitization of accelerograms recorded on film, and further processing of digitized or digitally recorded accelerograms using digital signal processing methods can be viewed as an estimation process of a signal embedded in noise, for which there is no exact answer, and which requires highly specialized operators able to make educated judgments depending on the application. The quality of digitization is currently limited mostly by the experience of the operator, and the rigor of quality control, rather than by the hardware. The optimal scanning resolution is 600 dpi, and is limited by the recording system (finite width of the light beam), and not by the capability of commercial scanners. Another limitation of the accuracy of processed data is that the instrument characteristics are rarely supplied in adequate detail to implement higher order instrument correction algorithms, and that the instruments are not calibrated periodically in field conditions. In this respect, the Los Angeles and Vicinity Strong Motion Network is a rare example of a network that has been fully recalibrated (including sensitivity constants and misalignment angles) in field conditions. Permanent displacements cannot be estimated reliably only from recorded three components of acceleration, and require simultaneous recordings of three components of rotation. Hence, until such recordings of six components of motion become available, high pass filtering is still the most reliable method of baseline correction. Finally, considering the large variability of ground motion from one point in space to another, compared to the accuracy of recording and data processing, especially in the near-field of moderate and large earthquakes, an order of magnitude larger spatial resolution of recordings is required for a significant progress in capturing these variations, which can be made possible only by a significant reduction of initial cost and cost of maintenance of strong motion instruments (Trifunac and Todorovska [19]).

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