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DIGITIZATION, DATA PROCESSING AND DISSEMINATION OF STRONG MOTION EARTHQUAKE ACCELEROGRAMS

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ABSTRACT

The modern techniques for digitization of strong-motion accelerograms and subsequent data processing were first developed in the late 1960s and early 1970s, at which time the only available digitization technology was semi-automatic hand digitization. Following the development of image processing technologies in the early 1970s, an automatic digitization and data processing system, driven by a mini-computer, was developed by Trifunac and Lee. The currently used digitization technology is based on personal computers and flat bed digital scanners, which appeared respectively in the early and late 1980s. The data processing part has been continuously evolving, thus improving the performance of the entire system. This paper presents a review of the developments in hardware and software for digitization of strong-motion accelerograms, data processing and data dissemination. In the 1980s, digital strong motion accelerographs became commercially available, and currently all new deployments are digital. However, it takes time to record a large number of strong motion accelerograms, and as of now, by far, most of the strong motion data has been recorded in analog form.

KEYWORDS: Digitization, Data Processing, Earthquake Accelerograms

INTRODUCTION

The first strong motion accelerographs were analog, and were built and installed at free-field sites and in buildings in the early 1930s. Soon after, strong motion was first recorded, on March 10, 1933, during the Long Beach, California earthquake. In the 1980s, digital strong motion accelerographs became commercially available (Trifunac and Todorovska, 2001a), and at present, essentially all new installations are digital. Yet, so far the largest number of strong motion records have been recorded in analog form, on light sensitive paper or on film. For analysis, analog strong motion records must be digitized and processed in a form suitable for subsequent analyses. This paper reviews the developments in digitization, processing (Trifunac et al., 1999a,1999b), and dissemination of strong motion accelerograms (Lee and Trifunac, 1982).

The concept of response spectrum as a tool in earthquake-resistant design was formulated in 1932, one year before the first recording of strong ground motion (Biot, 1932, 1933, 1934). Before the 1960s, spectra had to be computed with the aid of analog mechanical devices (e.g., torsional pendulum; see Biot, 1941, 1942) or electrical analog computers (Caughey et al., 1960). The modern era of digitization and processing of strong motion accelerograms started in the 1960s (Figure 1), with the availability of digital computers and semi-automatic digitizing machines (Hudson, 1979).

In the late 1960s and early 1970s, the only available technology for digitization of strong motion accelerograms was a semi-automatic, hand digitization system (Hudson, 1979; Trifunac and Lee, 1973). This system worked as follows. First, the film record (or its enlargement) was placed on the digitizing table, lining up by eye the horizontal axis to an estimated zero axis. The traces were digitized by placing manually the crosshair on successive points on the trace. The digitizer converted the coordinates to numbers, directly punched on cards or recorded on paper tape. A set of computer programs was then used to read and to plot the data on same scale as that of the original digitized record. This plot was checked against the original analog traces. Any errors found were corrected manually. This cycle was iterated until the final plot agreed well with the record. The raw data was then ready for routine computer processing (Trifunac and Lee, 1973).

The semi-automatic digitization system was operating from 1967 to about 1975. It was slow (it took about four days to digitize, check and load data onto magnetic tapes), accurate, and its noise characteristics were analyzed and documented (Trifunac et al., 1971, 1973a, 1973b). It was used to generate all the data published in the so-called Caltech "blue book data reports" (Hudson et al., 1969, 1971, 1972a, 1972b), which became the "standard" source for strong motion data all over the world. The digitized data of many famous older accelerograms in the blue book reports, such as March 10, 1933 Long Beach (Heck et al., 1936), May 18, 1940, El Centro (Trifunac and Brune, 1970), July 21, 1952, Taft (Hudson et al., 1969), and February 9, 1971, Pacoima Dam (Trifunac and Hudson, 1971), were all redigitized by Trifunac using this semi-automatic digitization system, because the previously digitized versions had inadequate sampling rate and occasionally missed or misinterpreted peaks in the strong motion part of the records.

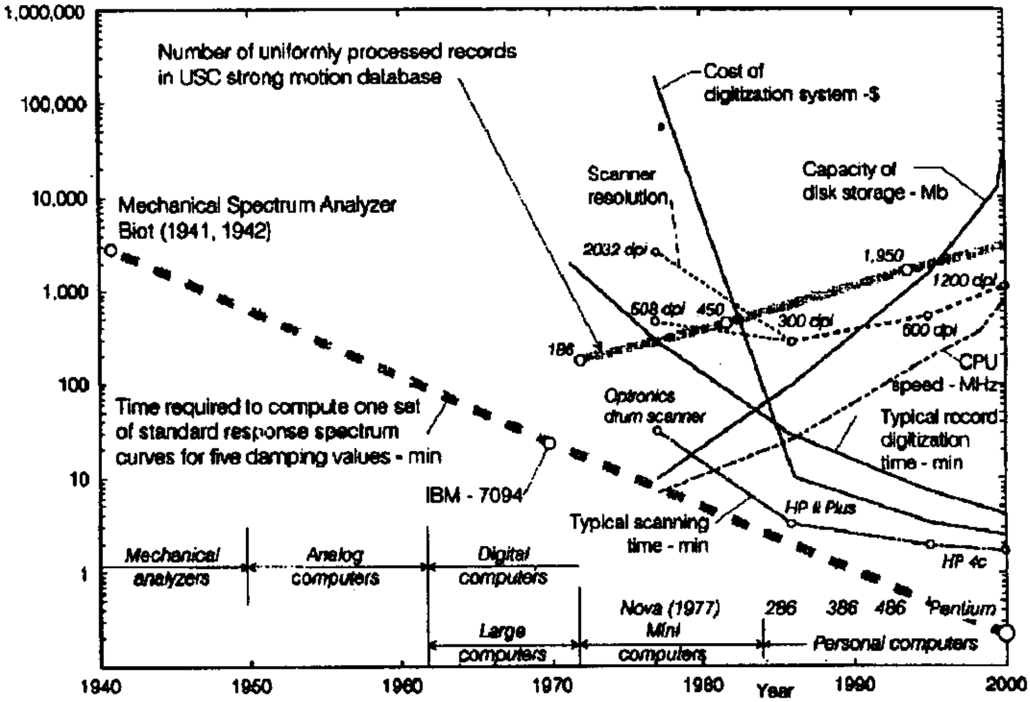

Fig. 1 Trends in capabilities and cost of accelerogram digitization and data processing systems

DIGITIZATION

1. The First Automatic Digitization System

The first automatic system for digitization of strong-motion accelerograms was developed by Trifunac and Lee (1979), using the commercially available hardware for image processing (Photoscan P-1000 photodensitometer by Optronics) and a Data General NOVA-3 minicomputer. With this system, up to four 10-inch sections of the accelerogram could be reproduced on a 10 × 10 in (254 × 254 mm) negative film (Figure 2), which was then placed onto the drum of the photodensitometar for scanning. It took only two to three hours to digitize a typical record using the new system, in contrast to several days on using the previous manual and semi-automatic systems. Another important difference was in the average sampling rate of the digitized record, which was 30 to 50 points per second for the old manual system, compared to greater than 200 points per second for the automatic system.

2. The New Automatic Digitization System

The first automatic digitization system (Trifunac and Lee, 1979; Trifunac, 1980) was modernized through the mid- and late 1980s, following the developments in personal computer hardware. The first digitization system in 1979 employed a photodensitometer table with a rotating drum (with cost over $30,000 at that time), and it had to be interfaced with a minicomputer, which was costly to acquire

($150,000) and expensive to maintain ($15,000 per year in 1976 and $7,000 per year in 1988). It used a Tektronix terminal ($12,000 in 1975), one of the best and the only high-resolution graphics terminal during the late 1970s.

In the 1980s, inexpensive high-speed personal computers (PCs) and desktop digital scanners appeared in the market and reduced the cost of the system to several thousand dollars (Figure 1). Our new software package "LeAuto," consisting of LeFilm, LeTrace, LeTV and LeScribe computer programs, now runs on a Pentiuum PC with 128 MB or more of RAM, running Windows98 or higher operating system, and with a fast Super VGA graphics monitor. The software has been continuously updated and improved to be compatible with the new scanners that have appeared in the market. By 2000, the cost of the hardware dropped to less than US $2,000 (Figure 1). The current resolution of digitization is > 200 points/s (assuming film speed of 1 cm/s), with gray levels resolved by 8, 10 or 12 bits (256, 1024 or 4098 gray levels) (Lee and Trifunac, 1990; Trifunac et al., 1999a, 1999b).

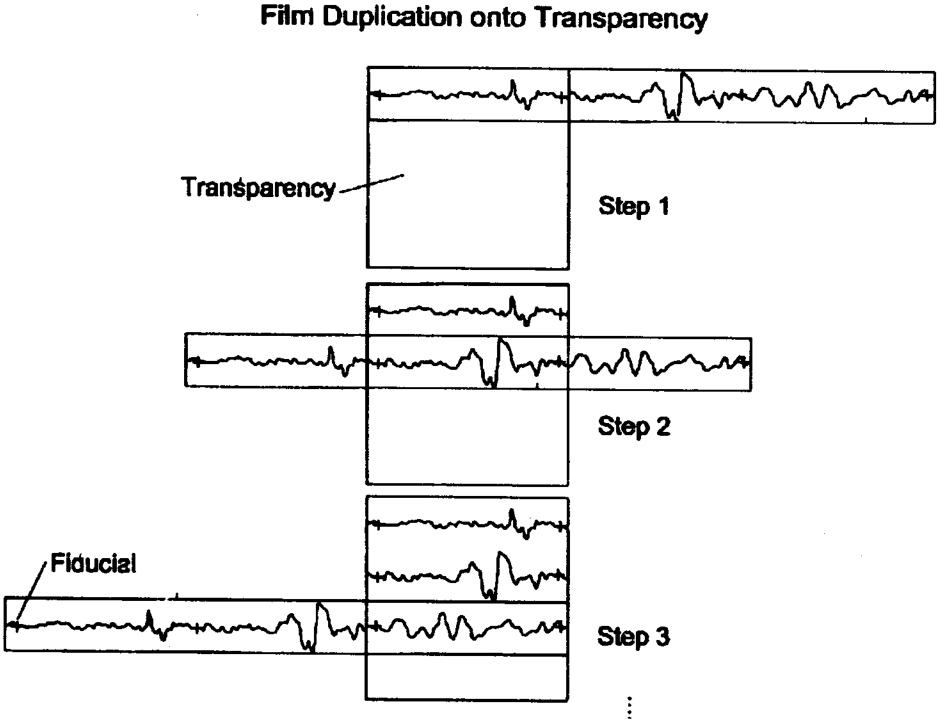

Fig. 2 Schematic diagram of duplication of original 70 mm film with recorded accelerogram, onto a 10 × 10 in (25.4 × 25.4 cm) negative, which is subsequently mounted on Optronics drum for scanning (Trifunac and Lee, 1979)

3. Hardware Components

The elements of the new automatic digitization system are shown schematically in Figure 3. The reading of an 8.5×11 inch film positive is performed by a Hewlett-Packard desktop digital scanner ("ScanJet"), interfaced with the PC. The PC needs to have a large hard disk drive and a minimum of 2 MB random access memory (RAM), while most modern PCs have 64, 128, 256 MB or larger RAM. In the early 1990s, the automatic digitization system ran on operating system DOS version 5.00 or higher (preferably DOS 6.2), and currently (early 2000s), it runs on Microsoft Windows 98 or higher operating system. The PC is interfaced with a Super VGA graphics display monitor, and a LaserJet printer, while other Windows-supported (e.g., DeskJet and InkJet) printers can also be used.

A typical strong-motion accelerogram is usually several tens of seconds long, but may be one minute or longer, if the complete length of useful recording is considered. Then, considering a typical SMA-1 70 mm wide film record, one would have to digitize a rectangular area 70 mm (2.75 in) wide and up to say 80 s (80 cm, 31.5 in) long. ScanJets are designed to scan a rectangular area up to 8.5×11 inches or 8.5×14 inches. Figure 2 shows a solution for handling long records, which was developed in the late 1970s for use with an Optronics rotating drum densitometer. A transparency film with fiducial marks was used, with the original accelerograph record copied in 10-inch long segments onto a rectangular negative (10 × 10 in), with up to four segments for simultaneous digitization.

At present, each 11-inch long segment ("page") is scanned by LeFilm and written onto consecutive disk files. Program LeTrace then processes (reads the scanned data and identifies the traces) each "page" sequentially. Using the program LeTV, the operator can edit each "page" one by one. The program LeScribe then reads the trace segments for each "page" and assembles them. This procedure thus enables one to digitize very long records. At present, LeFilm can also scan a 12-inch wide film records used by central recording system (CR-1), with 13 or more acceleration traces.

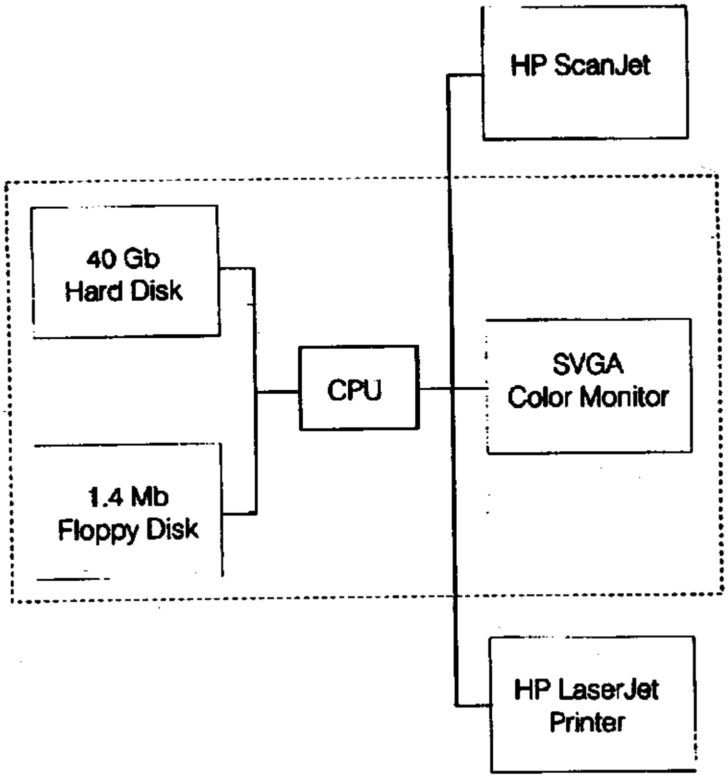

Fig. 3 Hardware components of the automatic digitization and data processing system

4. Noise Characteristics of the New System

The response and Fourier amplitude spectra of the digitization noise for the overall automatic digitization process are evaluated when the system is first assembled, and when it is upgraded. These spectra are used to determine the frequency range in which the signal-to-noise ratio for a digitized accelerogram trace is greater than unity, and which represents accurately the recorded motions. In general, the amplitudes of this noise depend on the scanner resolution, but also and mostly on the thickness of the trace and on the record length. Comparing records from acceleration and displacement transducers, Trifunac and Lee (1974) found that, for the old semi-automatic digitization, the typical digitization noise, after integration, might result in displacements up to several centimeters.

While for the old semi-automatic hand digitization system (Trifunac and Lee, 1973), the horizontal resolution (number of digitized points per unit length of the record) was a major factor determining the noise characteristics of the system, for the automatic digitization systems it is not, as the physical resolution (in pixels per mm) can be chosen sufficiently small not to affect the noise amplitudes. For the automatic system using Optronics photodensitometer (Trifunac and Lee, 1979), a resolution of 200 points/cm was sufficient (pixels 50 μ × 50 μ) for the noise amplitudes to depend mainly on the thickness of the traces. For the automatic system with a flat bed scanner used today, the typical resolution is 300, 600 or 1200 points/inch (dpi). Then, for 1 cm/s film speed and 600-dpi scan, the resolution is 236 points/s implying Nyquist frequency of 118 Hz which is more than sufficient for most recorded accelerograms.

The "noise acceleration traces" were created as follows. For several SMA-1 accelerograms, the pair of baselines was digitized and processed (scaled, instrument and baseline-corrected, and band-pass filtered between 0.07 and 25 Hz) considering one of them as a "zero" acceleration trace and the other one as a zero baseline, and response and Fourier amplitude spectra were finally calculated. Figure 4 (Lee and Trifunac, 1990) shows smoothed average spectral amplitudes for five damping values (0, 2, 5, 10 and 20 percent of critical) for 45 and 90 s long records. The overall spectrum amplitudes are similar to those for the automatic digitization system with an Optronics scanner (Trifunac and Lee, 1979).

A comparison of spectral amplitudes of noise of various recorders with those typical of recorded strong earthquake ground motion for magnitudes $4 < M < 7$ and for frequencies $0.1 < f < 20$ Hz is shown in Figure 5. It also shows nominal noise amplitudes for SMA-1, QDR and PDR accelerographs (Trifunac and Todorovska, 2001b).

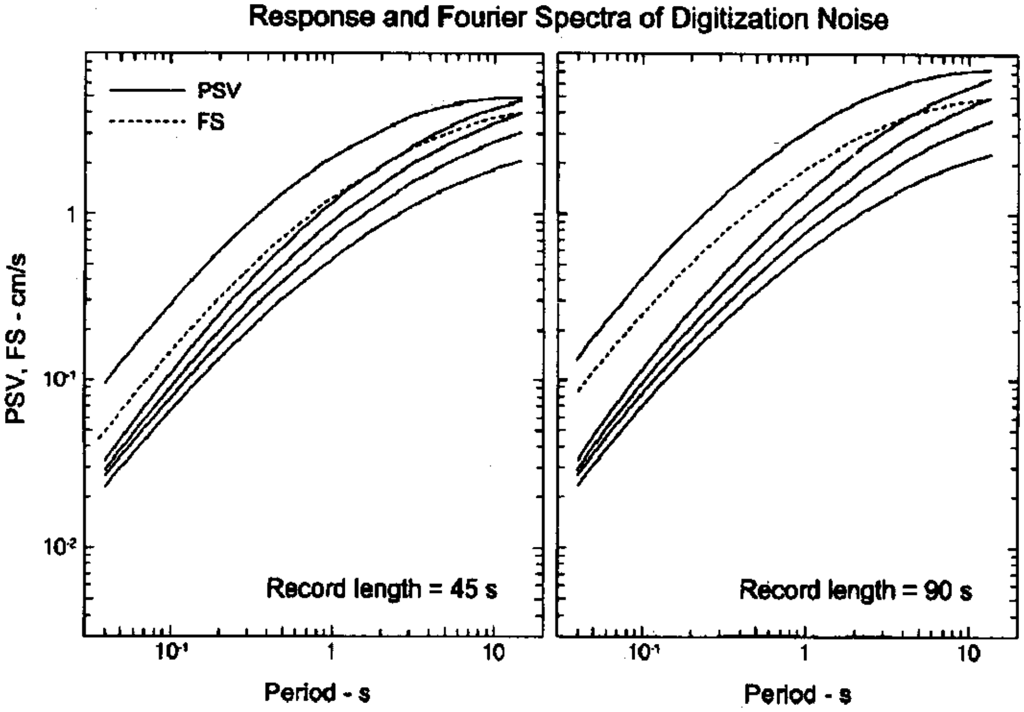

Fig. 4 Fourier spectra (dashed lines) and response spectra (solid lines) for damping $\zeta_0 = 0$, 0.02, 0.05, 0.10 and 0.20 (top to bottom), for records 45 seconds long (left) and 90 seconds long (right)

5. Capabilities of the Most Recent Automatic Digitization System

The current capabilities of the automatic digitization system, last upgraded in 2000/2001, have the following new features and capabilities:

(1) digitization with selectable 600-1200 (up to 2000) dpi resolution and up to 4096 levels of gray (upgraded from 256 levels of gray),

(2) possibility to scan up to 9 (8.5x11 inches) "pages" of a record sequentially, equivalent to 250 s (= 4.167 min) record length, for typical 1 cm/s film speed,

(3) possibility to scan wide (11 inches = 28 cm) records from central recording system with 13 or more acceleration traces.

The above increase in resolution of scanning equipment does not necessarily indicate an improvement in the quality of digitized accelerogram (Trifunac et al., 1999b), but may help identify high frequency content of a record.

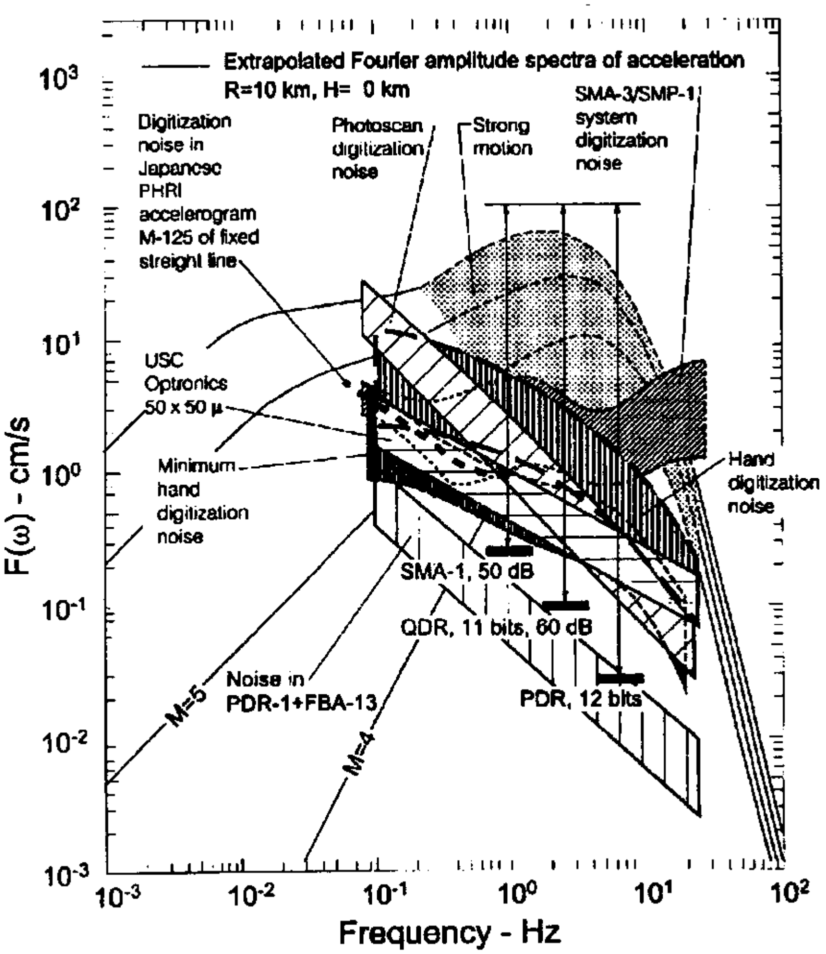

Fig. 5 Comparison of different noise spectra associated with different recording instruments and different methods of digitization (modified from Trifunac and Todorovska, 2001b)

6. Advanced Digitization and Raw Data Pre-processing

6.1 Accurate Selection of the Trace Onset

The position of the first digitized point of an acceleration trace determines the origin of its time coordinate. Because of the common trigger mechanism, all the three traces (*L*, *V* and *T*) start to be recorded simultaneously, but if the first point is not digitized properly, there will be a time delay in the digitized time series. Synchronization of the origin time and of the running time scales for all the components on a film record is crucial for many applications, for example in inverse analyses of the earthquake source mechanism ("random" time delays in the digitized data affect the numerical stability of the inversion), applications that require linear combination of the recorded components of motion, such as computation of the radial and transverse components of motion (affect the accuracy of peak amplitudes in the rotated directions; Todorovska and Trifunac, 1997), in analyses of building response from wave propagation viewpoint, or in correction of accelerograms for cross-axis sensitivity and transducer misalignment (these corrections are meaningless unless the three components are synchronized; Todorovska, 1998; Todorovska et al., 1995, 1998; Wong and Trifunac, 1977).

One way to reduce these errors is intervention by the operator who can choose manually the first point, but this is time consuming and is subjective. To increase the efficiency of this step and to eliminate subjectivity, in 1994 we introduced an algorithm that determines automatically the "best" starting point for each acceleration trace. This algorithm was tested on hundreds of accelerograms, and was found to be successful (error less than one pixel) in about 95% of cases). Difficult cases would still require operator intervention (Trifunac et al., 1999b). An example of a circumstance that can complicate this task is when the gap between the end of the previous record and the onset of the current record is too short or the traces overlap, so that they appear as continuous on the scanned image. When such traces are displaced (i.e. the trace starts with a large amplitude), this problem is eliminated (Trifunac et al., 1999b).

6.2 Non-uniform Film Speed

The nominal film speed for typical strong motion accelerographs is 1 cm/s (SMA-1, CR-1). For the M02 accelerograph used in New Zealand, which records on a 35 mm film, the actual film speed is 1.5 cm/s, which is equivalent to 3 cm/s for a 70 mm film (SMA-1). Increasing the film speed improves the resolution and accuracy of digitization of the high frequency accelerations not only in time, but also in amplitude. The old AR-240 accelerograph (which recorded the Pacoima Dam accelerogram during the 1971 San Fernando, California, earthquake) had a recording speed of 2 cm/s (equivalent to 0.5 cm/s on a 70 mm film; Hudson, 1970).

Most instruments have one or two relays which produce two-pulses-per-second (2PPS) signals recorded along the top and bottom edges of the film or paper. About 20 years ago, one of these relays was converted to work with a local clock which produced a binary code of the Julian day, hour, minute and second, every 10 s. At first, it was believed that absolute trigger time was not necessary for recorded strong ground motions (Hudson, 1970), but since it was first introduced in the early 1970s (Dielman et al., 1975), it opened many new possibilities for advanced wave propagation studies in strong motion seismology.

The 2PPS signal accuracy is believed to be within ~ 1% of nominal, but it is rarely calibrated. Since the early 1970s, we have assumed that the time coordinate of analog records is scaled more accurately using 2PPS pulses (generated electronically) rather than by the nominal speed of the film (driven mechanically), and have used it to correct for minor variations in the film speed (Lee and Trifunac, 1990; Trifunac and Lee, 1973, 1979). Exceptions are records for which the 2PPS and absolute clock relays malfunctioned simultaneously (e.g. see Trifunac et al., 1999a).

Occasionally, the film speed may experience abrupt changes and stalls. This is caused by friction in the film driving mechanism, friction in the film cassette or by faulty motors, and in general cannot be corrected uniquely. The duration of short stalls can be estimated by measuring the shortening of the distance between consecutive pulses of the 2PPS signal. The digitized data then can be corrected approximately, by inserting "gaps" into the scanned bitmap image, and by recreating manually the missing portion of the traces (Lee and Trifunac, 1984). A description of processing an accelerogram with many stalls can be found in Trifunac et al. (1999a).

DATA PROCESSING

1. Previous Work

The data processing of strong-motion accelerograms evolved alongside with digitization of analog records, after the first earthquake accelerogram was recorded on March 10, 1933, during the Long Beach earthquake in California. This remarkable event, which triggered numerous pioneering accomplishments in strong motion instrumentation, was commemorated during the 50th anniversary of strong-motion seismology at the University of Southern California in Los Angeles (Hudson, 1984). Through the 1930s, 1940s and 1950s, there were only a dozen or so recorded "significant" strong motion accelerograms (Biot 1941, 1942; Hudson, 1976, 1979). The accelerograph data processing then required lengthy manual calculations, or the use of analog computers (Biot, 1941). The 1960s marked the beginning of the rapid growth in the number of recordings and of the development and use of digital computers. With these, new methods associated with digital data processing slowly gained in speed, accuracy, access and popularity. In the early 1970s, after the 1971 San Fernando earthquake in California, the large number of recorded accelerograms, and the need of many investigators to compare their results on a common basis, finally resulted in the need for a systematic development of routine data processing of strong-motion accelerograms (Hudson et al., 1969, 1971, 1972a, 1972b).

The first systematic development of routine computer programs for processing strong-motion earthquake accelerograms was completed in the early 1970s (Trifunac and Lee, 1973). Almost all of the records then were in analog form and were digitized manually (on Benson-Lehner 099D digitizer), which is the case for the records from the 1971 San Fernando earthquake (Hudson, 1976). The routine data processing software was then developed for the manual digitization scheme. The computer programs (Trifunac and Lee, 1973) were first written for the IBM 7094 and IBM 360 computers. These programs involved the following steps:

(i) Volume I Processing (scaled data; Hudson et al., 1969): The half-second timing marks are first checked for "evenness" of spacing, and then smoothed by a (1/4, 1/2, 1/4) running average filter. The x-coordinates of each trace are next scaled to units of time in seconds. Each fixed trace (baseline) is smoothed and subtracted from the corresponding acceleration trace, with the y-coordinates subsequently scaled to units $g/10$ ($g = 9.81$ m/s^2).

(ii) Volume II Processing (corrected data; Hudson et al., 1971): The scaled uncorrected Volume I acceleration data is next corrected for instrument response (Trifunac, 1972) and baseline adjustment (Trifunac, 1970, 1971). The data is first low-pass filtered with an Ormsby filter having a cutoff frequency $f_c = 25$ Hz and a roll-off termination frequency $f_t = 27$ Hz. Instrument correction is next performed using the instrument constants. These constants are the natural frequency and ratio of critical damping of the instrument, which is considered as a single-degree-of-freedom system (Trifunac and Hudson, 1970; Todorovska, 1998). These are determined from calibration tests for each accelerograph transducer. The data is then baseline-corrected by a high-pass Ormsby filter. The cutoff and roll-off frequencies of the filter are usually determined from the signal-to-noise ratio of each component (Trifunac and Lee, 1978). The acceleration data is then integrated twice to get velocity and displacement. To avoid long period errors resulting from uncertainties in estimating the initial values of velocity and displacement, the computed velocities and displacements are high-pass filtered at each stage of integration, using the Ormsby filter with the same cutoff and roll-off frequencies as for the corrected accelerogram (Hudson et al., 1971).

(iii) Volume III Processing (response spectra; Hudson et al., 1972a): Using an approach based on an exact analytical solution of the Duhamel integral for successive linear segments of excitation, the Fourier and response spectra for up to 91 periods and 5 damping ratios are calculated. The times of maximum response for all periods and damping ratios are also recorded (Lee and Trifunac, 1979, 1986).

Following the development of the automatic digitization system (Trifunac and Lee, 1979), the above computer programs, originally developed in 1969/70 (Trifunac and Lee, 1973), were modified in 1978/79 (Trifunac and Lee, 1979) to run on a Data General mini computer. The new approach, which took advantage of image processing techniques, increased the speed of the overall data processing by one order of magnitude (Figure 1).

(iv) Volume IV Processing (Fourier amplitude spectra; Hudson et al., 1972b): Using the Fast Fourier Transform (FFT) algorithms (Cooley and Tukey, 1965; Udwadia and Trifunac, 1977) for applications that require equally spaced data on Fourier amplitude spectra, Volume IV data were computed and presented in the series of "Blue Book Data Reports" since 1972. This data was used in numerous empirical studies of Fourier spectrum amplitudes. It offered an opportunity to routinely identify significant frequencies in the records using Fisher (1929) test of significance in harmonic analyses. At present, Volume IV data processing is not performed routinely because of the high speed with which FFT can be calculated with modern computers, as required for each particular application.

2. The Current System

In general, the principles and the requirements governing the routine data processing of strong-motion records have changed little, if any, since the early 1970s. However, since then, we have witnessed a remarkable progress in digital signal processing techniques, in their accuracy, efficiency, speed of execution and in the major hardware cost reduction. These improvements have been incorporated into the routine data processing of strong-motion accelerograms (Lee and Trifunac, 1984, 1990). The currently used system, along with the automatic digitization system, runs on a Windows PC.

3. Volume II Low-Pass Filtering

Low-pass filtering is performed to eliminate the high-frequency digitization errors. The design of low-pass filters is well documented in digital signal processing textbooks (Gold and Rader, 1975; Rabiner and Gold, 1975; Hamming, 1977). These filters are divided into two main groups according to their design: Finite Impulse Reponses (FIR) and Infinite Impulse Response (IIR) filters. The Ormsby filter, first introduced in strong-motion accelerograms processing by Trifunac (1970, 1971), is a FIR filter. The elliptic (Sunder, 1980) and Butterworth (Converse, 1984) filters, also proposed and used in accelerogram data processing, are IIR filters.

Strong motion consists of transient body and of dispersed surface waves, and therefore to preserve its physical nature and enable analyses of its phases, all data processing operations on recorded accelerograms must not alter the original phase. The FIR filters can be designed to have zero phase shift, so as not to introduce a phase shift between the recorded and processed signal. The IIR filters, on the other hand, do introduce phase shift. To "cancel" this phase shift, a time reversal technique has been used (Rabiner and Gold, 1975). However, at the beginning of time series, it takes time for an elliptic filter to "settle" down after a sudden change in the input. The non-recursive Ormesby filter, on the other hand, has much smaller transient response. Because of such problems, and because of instabilities and phase shifts, the recursive filters tend to be used only for very long signals, which are more or less stationary in character. The non-recursive filters are simpler to understand, design, and use, and are more suitable for signals that are more transient in nature, as strong motion accelerograms, for example.

The transfer function of an elliptic IIR filter also has ripples in both the pass-band and stop-band. Ripples are tolerated in the design for optimality in the order of the filter. Processing of strong motion accelerograms involves consecutive application of many filters. Besides the low- and high-pass filtering, the instrument correction also involves application of a differentiation filter twice (to compute the first and second order derivatives of the signal), and the integration performed to compute velocity and displacement involves double application of an integration and a high-pass filter. If the signal passes through M such filters, each with ripple amplitudes $(1 + \varepsilon)$ in the passband, the resulting ripple peaks will have amplitude $(1 + \varepsilon)^M$, and may be confused with real ripples in the data. Ripples in the passband are thus not desirable in signal processing involving many consecutive filters (Lee and Trifunac, 1989). Ripples in the stopband are not desirable for the same reason. This problem can and should be avoided by using filters that vary smoothly throughout their pass-band. A set of design criteria for low-pass filters for processing accelerograms can be found in Lee and Trifunac (1990). A good general discussion of guidelines and a comparison of the performance of FIR and IIR filters can be found in Hamming (1977).

4. Volume II-Instrument Correction

A seismometer or an accelerometer usually records the relative displacement or velocity response of its transducer mass. Instrument correction is then applied to remove the effect of the transducer transfer-function on the recorded signal $y(t)$ and to compute the input ground motion $x(t)$. For most strong-motion accelerographs, the dynamic equation of motion of the transducer as a single-degree-of-freedom system is

$$\ddot{y} + 2\zeta_0\omega_0\dot{y} + \omega_0^2 y = -\ddot{x} \tag{1}$$

where $x(t)$ is the input displacement, $y(t)$ is the relative displacement of the transducer mass, ω_0 is the natural frequency of the transducer, and ζ_0 is the fraction of critical damping. Hence, the instrument correction involves numerical differentiation.

Many differentiation filters are available, including the central difference scheme and other higher-order formulae. The filter used should have zero phase-shift and result in no phase-distortions. The transfer function of the filter should be purely imaginary, as the ideal differentiation filter has transfer-function $\mathrm{H}(\omega) = i\omega$. Design criteria for a differentiation filter for instrument correction can be found in Lee and Trifunac (1990).

There are other accelerometers and seismometers with transducers that do not behave as a mechanical single-degree-of-freedom system (Novikova and Trifunac, 1991), and will thus require specialized instrument correction algorithms. Lee and Wang (1983) developed an instrument correction algorithm for the RDZ1-12-66 strong-motion pendulum galvanometer produced in China, and Novikova and Trifunac (1991) developed an algorithm for coupled transducer-galvanometer systems, which have produced a large number of records, for example, in former Soviet Union. Novikova and Trifunac (1992) also developed instrument correction algorithms for a force-balance accelerometer (FBA) (Amini and Trifunac, 1983, 1985; Amini et al., 1991).

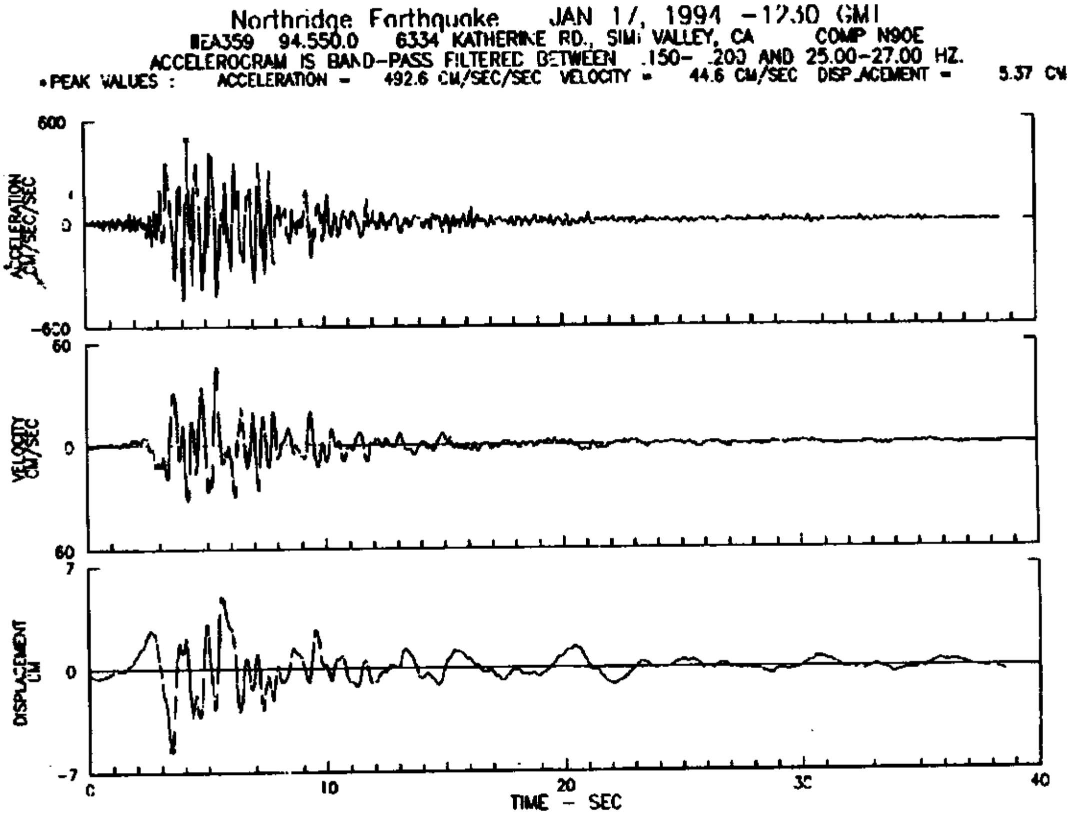

Fig. 6 Typical output from Volume II processing: corrected accelerogram and integrated velocity and displacement versus time

5. Baseline Correction and Noise-Free Frequency Band

Accelerograms low-pass filtered and corrected for the instrument transfer-function are next baseline-corrected by high-pass filtering, to remove the long period recording and processing noise. The record is initially high-pass filtered with cutoff frequency of 0.07 Hz, corresponding to cutoff period of ~14 s which is sufficiently long for most strong-motion accelerograms (Trifunac et al., 1973a, 1973b). The final cutoff frequency is later determined separately for each acceleration trace from the signal-to-noise ratio (Trifunac and Lee, 1979).

For a trace digitized at 200 points/s sampling rate, the Nyquist frequency is 100 Hz. Then, high-pass cutoff frequency of 0.1 Hz implies ratio between the highest and the lowest frequency of 1/1000 and a very small fraction of the whole frequency band of the data. This constitutes a narrow band filtering or a narrow band rejection.

An IIR elliptic/Butterworth filter (Converse, 1984) has been proposed to replace the FIR Ormsby filter (Trifunac and Lee, 1979), but, as discussed earlier, it distorts the phase of the output signal, unless a time reversal technique is used. Lee and Trifunac (1984, 1990) proposed an efficient implementation of narrow-band filtering using the algorithm of Rabiner and Crochiere (1975), which involves decimation followed by interpolation, using FIR filters, and this was implemented in their accelerogram processing software.

The next step is to determine the appropriate high-pass cutoff frequency for each trace, based on the signal-to-noise ratio. When the routine data processing software was first developed, all records were band-pass filtered between 0.07 and 25 Hz (Trifunac, 1971). These cutoff frequencies were based on a detailed study of the digitization error of the system available in the early 1970s (Trifunac et al., 1973a, 1973b), and do not apply to records digitized with different systems. Also, smaller amplitude accelerograms may require a more restrictive lower cutoff frequency, depending on its signal-to-noise ratio (Amini et al., 1987; Lee et al., 1982; Trifunac, 1977; Trifunac and Lee, 1978).

In the early stages of the development of routine accelerogram processing software, it became clear that the optimum cutoff frequencies had to vary from one record to another, if one were to eliminate all the significant noise from the digitized data. Trifunac and Lee (1978) considered a batch of 186 records of uniformly processed earthquake ground acceleration recorded in the western United States of America for the period 1933-1971. These were again band-pass filtered with frequencies predetermined by visual inspection to maximize the signal-to-noise ratio within the band. Of the 186 records or 558 components considered, 69% were originally processed with the standard 15 s (0.07 Hz) long period cutoff, and the remaining 31% with 8 s (0.125 Hz) long period cutoff. Following the requirement for uniform signal-to-noise ratio, as much as 50% of the records routinely filtered at 15 s were refiltered with a shorter long period cutoff ranging from 1 to 15 s. Similarly, about 12% of the records, routinely filtered at 8 s were refiltered with cutoff periods ranging from 1 to 8 s.

In the late 1970s and early 1980s, in the routine data processing software, a subroutine was included that determined automatically the cut-off frequencies for each individual acceleration trace based on the signal-to-noise ratio, and the record was then refiltered. This resulted in processed data with a variable, higher than 0.07 Hz, cutoff frequencies, depending on the amplitudes of the record, which in turn depend on the magnitude of the earthquake, local geology and distance from the source (Lee et al., 1982).

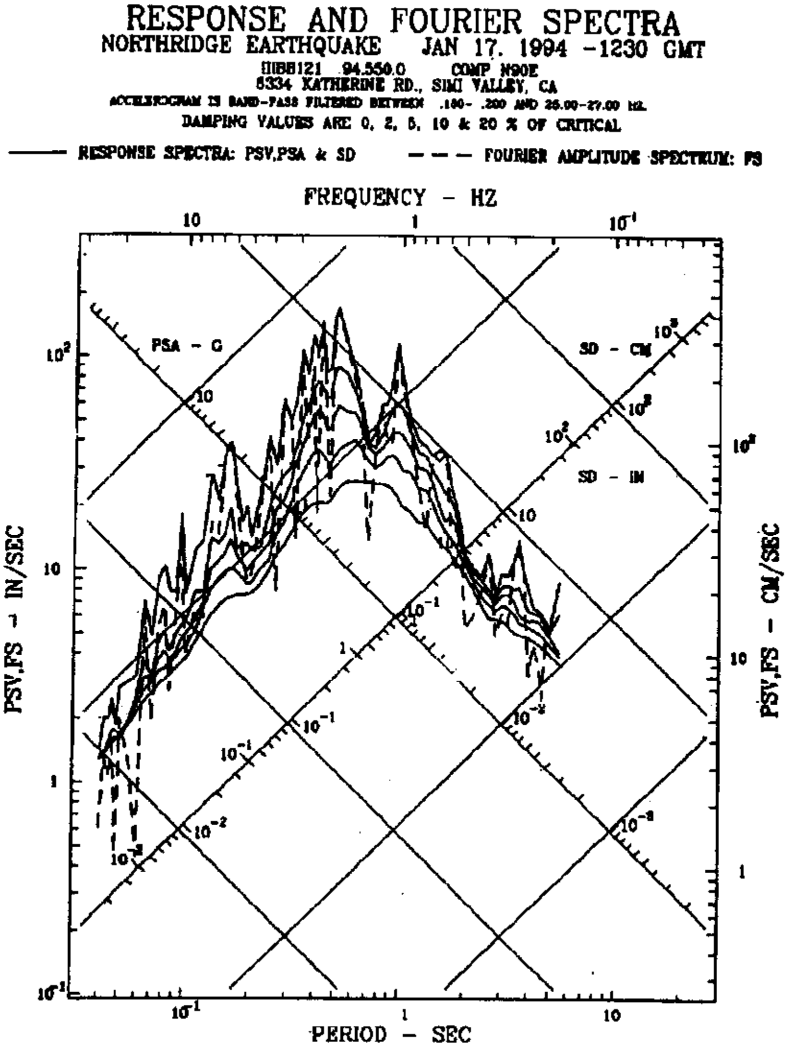

Fig. 7 Typical output from Volume III processing: Fourier (dashed) and pseudo relative velocity spectra for five damping values $\zeta_0 = 0, 0.02, 0.05, 0.1$ and 0.20 (top to bottom)

6. Integration and Response Calculations

The next step is integration of the instrument-corrected and band-pass filtered acceleration twice to get velocity and displacement. Many integration filters are available, including the trapezoidal rule and other higher order formulae. The filter used should have phase $-\pi/2$ as the ideal integrator $H(\omega) = 1/(i\omega)$, so that there is no phase distortion. Sunder (1980) proposed a 7-term integration formulae (Schussler-Iber) which does not have phase $-\pi/2$, thus resulting in phase-distorted output. A set of design criteria for integration of a digital signal, to obtain velocities and displacements from acceleration, can be found in Lee and Trifunac (1990).

There exist efficient algorithms for the calculation of velocity and displacement from acceleration (Lee, 1984, 1990), but we prefer to use the original algorithm (Nigam and Jennings, 1969; Hudson et al., 1971; Trifunac and Udwadia, 1979) based on exact integration of piecewise straight line representation of an accelerogram with equally spaced points. Figure 6 shows a plot of the corrected acceleration, velocity and displacement for one typical component of an earthquake record.

The next step consists of the computation of response spectra at discrete periods and for five damping values (Hudson et al., 1972a). Figure 7 shows a plot of the pseudo relative velocity (PSV), relative displacement (SD), and pseudo acceleration (PSA) response spectra on a tripartite logarithmic plot. Such a tripartite plot is possible because of the relationship between PSV, SD and PSA (Hudson et al., 1972a).

HIGHER-ORDER CORRECTIONS

So far in this paper, the standard data processing algorithms were described, which are suitable for routine, large scale processing of analog strong motion records. For specialized studies requiring higher accuracy, further corrections may be required. In the following, we describe two such corrections.

1. Misalignment and Cross-axis Sensitivity

In routine data processing of three-component acceleration records, it is assumed that the three sensitive axes (longitudinal, transverse and vertical) are mutually perpendicular. Careful tilt table measurements show however that this is not so and that each sensitivity vector can be misaligned by small (few degree) angles (Todorovska, 1998; Todorovska et al., 1995, 1998; Wong and Trifunac, 1977). For accelerometers, which are sensitive to static tilt, the misalignment angles can be measured by simple tilt tests followed by data processing (Todorovska et al., 1995, 1998). These angles then can be used to perform exact corrections of cross-axis sensitivity and misalignment, resulting in corrected accelerations along three mutually orthogonal coordinate axes.

Measurements of the misalignment angles and corrections for misalignment and cross-axis sensitivity have been performed for all instruments of the Los Angeles strong motion network (Todorovska et al., 1998) and for the stations of the Los Angeles Department of Water and Power (Todorovska et al., 1999) for strong motion data recorded during and following Northridge, California earthquake of 17 January, 1994.

2. Corrections for Tilt and Angular Accelerations

Let X_1, X_2 and X_3 be the mutually perpendicular coordinate axes of displacement in longitudinal (L) Transverse (T) and Vertical (V) directions, and let ϕ_1, ϕ_2 and ϕ_3 represent the rotations about X_1, X_2 and X_3 directions. For small transducer deflections $y_i = r_i\alpha_i$ where α_i is the angle of deflection of the i-th pendulum from its equilibrium position, and r_i is its corresponding lever arm, the equations of motion of the three penduli of an accelerometer (e.g. SMA-1) are (Todorovska, 1998):

$$\mathrm{L}: \ddot{y}_1 + 2\omega_1\varsigma_1\dot{y}_1 + \omega_1^2 = \ddot{X}_1 + \phi_2 g - \ddot{\phi}_3 r_1 + \ddot{X}_2\alpha_1 \tag{2a}$$

$$\mathrm{T}: \ddot{y}_2 + 2\omega_2\varsigma_2\dot{y}_2 + \omega_2^2 y_2 = -\ddot{X}_2 + \phi_1 g - \ddot{\phi}_3 r_2 + \ddot{X}_1\alpha_2 \tag{2b}$$

$$\mathrm{V}: \ddot{y}_3 + 2\omega_3\varsigma_3\dot{y}_3 + \omega_3^2 y_3 = -\ddot{X}_3 - \ddot{\phi}_1 r_3 - \ddot{X}_2\alpha_3 \tag{2c}$$

where ω_i and ζ_i are respectively the natural frequency and fraction of critical damping of the i-th transducer. The second and third terms on the right hand side of Equations (2a) and (2b) represent contributions from tilting (ϕ_1 and ϕ_2) and angular acceleration ($\ddot{\phi}_3$) to the recorded responses y_1 and y_2. The tilting of an instrument does not contribute to the linearized equation for y_3 (Equation (2c)), but the angular acceleration ($\ddot{\phi}_1$) does. The last terms on the right hand side in all three equations are contributions to the response from cross-axis sensitivity.

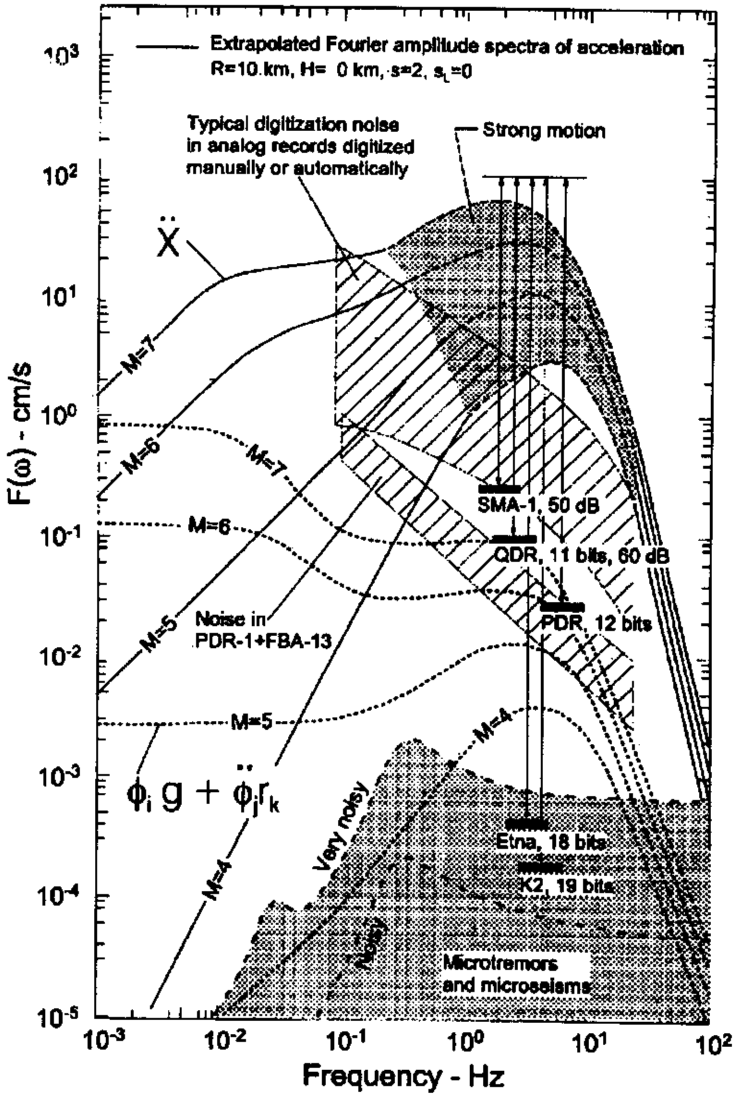

Fig. 8 Comparison of Fourier amplitude spectra of translation, $\ddot{X}_i$ with spectra of contribution from $\phi_i g+\ddot{\phi}_j r_k$, analog digitization noise, digital digitization noise (PDR), and microtremor and microseism noise (redrawn from Trifunac and Todorovska, 2001b)

Figure 8 shows a comparison of Fourier amplitudes of $\ddot{X}_i$ and of $\phi_i g+\ddot{\phi}_j r_k$, at epicentral distance R = 10 km, for magnitudes $4 \le M \le 7$, and for frequencies $10^{-3} \le f \le 10^2$ Hz. It shows that for analog records from SMA-1 accelerographs, for example, the contributions of $\phi_i g+\ddot{\phi}_j r_k$ are smaller than the digitization noise and can be neglected. For recorders with resolution higher than about 12 bits (e.g., PDR-12 bits; Etna-18 bits; K2-19 bits; see Trifunac and Todorovska, 2001b), the contribution of $\phi_i g+\ddot{\phi}_j r_k$ terms cannot be neglected. This means that for the instrument and baseline correction of digital accelerographs, the recorded data on ϕ_i and $\ddot{\phi}_i$ must be provided simultaneously with the records of y_i, so that correct $\ddot{X}_i$ can be calculated. Without ϕ_1 and $\ddot{\phi}_i$, accurate estimation of $\ddot{X}_i$ is not possible. In other words, the data from high-resolution digital accelerographs will be represented by the entire right hand side of Equation (2), not just $\ddot{X}_i$. This means that recording with high-resolution (higher than about 12 bits) accelerographs will be meaningful only if all three translations X_i and three rotations ϕ_i are recorded simultaneously (Trifunac and Todorovska, 2001b). Assuming that such recordings are available in future, it will be possible to formulate the required instrument and baseline correction procedures.

DATA DISSEMINATION - EQINFOS SYSTEM

The first computerized dissemination system for strong motion data was the EQINFOS system (Strong Motion Earthquake Data Information System), developed by Lee and Trifunac (1982) in the early 1980s, years before the Internet and modern electronic communication capabilities. It operated on Data General, Eclipse S/130 mini computer. It (1) provided data to the users via ordinary telephone lines and acoustic modems, (2) allowed outside users to use the data processing software at USC laboratory and (3) provided means for remote data digitization and processing. Software was provided for off-line plotting, printing and data storage. The system also maintained a searchable uniformly processed strong motion database on disk (Trifunac and Lee, 1978; Trifunac, 1977). This database could be searched by selecting geographic coordinates, time of occurrence, geologic and soil site conditions at the recording site, peak amplitudes, magnitude range, or Intensity range, for example.

We also initiated the development of EQINFOS-compatible strong motion databases for different parts of the world. In the first set, we included all strong motion data recorded at free-field stations in the western U.S. between 1933 and 1984 (Lee and Trifunac, 1987). This was followed by a database recorded in former Yugoslavia, between 1975 and 1983 (Jordanovski et al., 1987), in Bulgaria, between 1981 and 1987 (Nenov et al., 1990), in India between 1967 and 1991 (Gupta et al., 1993; Chandrasekaran et al., 1993), and the Northridge 1994 earthquake and its major aftershocks, in California (Todorovska et al., 1999).

By extensive empirical studies based on these databases during the past 20 years, we found that the EQINFOS data formats and the accompanying cross-referencing tables are suitable and complete for most of the modern earthquake engineering research. With rapid developments of the Internet and wide-spread use of the World Wide Web, at present we are expanding and generalizing the use of EQINFOS concept to the modern web applications. Our web site at http://www.usc.edu/dept/civil_eng/Earthquake_Earthquake_eng/ is now used to store and distribute the strong motion data, we recorded with Los Angeles strong motion array (Trifunac and Todorovska, 2001a), or gathered from other sources.

CONCLUSIONS

In this paper, we summarized the historical developments that led to the present capabilities for digitization of analog film or paper records, data processing and dissemination. In future with further developments in digital recording, the need for image processing of analog records will diminish, but considering the volume of analog recordings so far, it may take many years before all this data is available in digital form.

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