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Determination of noise spectra from strong motion data recorded in Greece

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Abstract

A large number of strong ground motions in Greece have been recorded by analog accelerographs. The processing of analog strong motion recordings and conversion to a digital form introduces noise in the signal, due to the digitization and processing which significantly affects the record. In the present paper a unified processing and determination of digitization and processing noise for the Greek strong motion records is presented. Moreover, appropriate relations are proposed for the lower cut-off frequency with respect to the epicentral distance and earthquake magnitude for record filtering.

Introduction

Ground motion records from strong earthquakes make a significant contribution to our knowledge on earthquake engineering in seismic active areas, as well to our study of seismic wave propagation. A large number of accelerograms have been recorded in analog form film or paper. The conversion of these records into digital signals requires digitization and appropriate correction. Due to methods applied for recording, digitizing and processing of the records, noise is introduced in the signal which notably affects the credibility of the record components, mostly in low but also in high frequencies. This process usually results in the reduction of the useful frequency bandwidth from which we can derive reliable information (Trifunac et al., 1999; Amini et al., 1987).

This is very important for the low frequency signals which are the ones mostly affected by the spectral features of the noise due to digitization and processing of the record (Hudson, 1979). It should be noted that low frequency seismic waves have a great contribution in the response of tall buildings and large constructions, such as bridges and dams, hence have a special importance for engineering seismology.

Since it is necessary to use strong motion records which do not depend on the recorded noise level, a need for studying the noise characteristics in different recording systems or the noise level introduced during the processing of strong motion records has originated. Several techniques for processing of analog accelerograms have been developed in order to eliminate or reduce the presence of repetitive errors in ground motion recordings. Trifunac and Lee were the first to develop such techniques (Trifunac and Lee, 1974; Lee and Trifunac, 1984, 1990), while some modifications have been suggested by a number of authors (Basili and Brady, 1978; Shoja-Taheri, 1980; Sunder and Connor, 1982; Crouse and Matuchka, 1983; Rinaldis et al., 1994). In the present work the results of the processing of 420 records of strong motion data recorded in Greece are presented. A robust method for processing and estimating the noise due to the digitization and processing of the records is suggested. Also a relation for the estimation of the average noise for Greece is introduced. Finally relations are proposed for reliable estimation of the lower spectral limit (low cut-off frequency) for the filtering of analog strong motion records.

Instrumentation and strong motion records

The most common recording instruments in Greece are the Kinematrics analog accelerographs SMA-1, which consisted until the end of 2002 the backbone of ITSAK's (Institute of Engineering Seismology and Earthquake Engineering) main accelerograph network. All the records used in this work have been collected from this network. SMA-1 records must be digitized with a semi-automatic or an automatic procedure (Sabeta, 1985; Basili, 1987; Margaris, 1994). This digitization results in significant noise introduction, especially in the lower frequencies of the signal, resulting in a smaller frequency bandwidth for which reliable information can be obtained compared to data recorded from digital accelerographs (Margaris, 1994).

The first correction usually applied in the digitized records is the baseline correction (Lee, 1989). Baseline errors are mostly due to the deformation of the film and other similar recording problems and results in the introduction of low frequency noise. Generally, a small shift of the baseline in accelerograms' waveform produces a false linear trend in the velocity's waveform baseline and second order term trend in the displacement. A simple technique to correct this problem is the subtruction from the acceleration waveforms of a straight line calculated with the least squares method. A more sophisticated way of eliminating such errors is the three-step routine proposed by Hung (1997).

Processing of strong motion records

In order to remove all previously mentioned errors and obtain an accurate description of ground parameters (acceleration, velocity and displacement), various correcting procedures of accelerograms have been developed. The procedure usually relies on the use of appropriate digital filters. In the present paper the following low-pass filter was used:

$$H(f) = 0 \quad |f| \geq f_c$$

$$H(f) = \frac{|f| - f_c}{f_r - f_c} \quad f_c > |f| f_r \tag{1}$$

$$H(f) = 1 \quad |f| \leq f_r$$

where f_c and f_r are cut-off and roll-off frequencies, respectively. Similar equations can be used for the high-pass filter. In practice, the processing of strong motion data relies on the comparison of the Fourier spectrum of the recorded components and the corresponding noise spectrum, which allows us to estimate the frequency bandwidth that gives us reliable results. By applying a band-pass filter for this bandwidth we obtain the corrected data, which are partly free from noise. The estimation of the noise spectrum is based on the digitization and processing of two components of the film, which are produced from a non-oscillating light beam or pen (depending on the recording media of the accelerograph) and represent the zero acceleration components of the record, usually referred as fixed traces.

For the estimation of the characteristic frequencies of the high-pass filters that will be applied on the uncorrected data, an appropriate processing program was written, which uses the Fourier amplitude spectra and calculates the frequencies for which the signal to noise amplitude ratio exceeds a certain threshold such as 2:1, 3:1, etc. After testing different filters for the records, we have chosen as cut-off frequency f_c, the frequency where signal to noise ratio was 2:1 and for roll-off frequency f_r, the frequency where signal to noise ratio was 3:1 (see equation 1).

The data used in the present work correspond to records from ITSAK's accelerograph network for a period of seventeen years between 1980 and 1997. From all the available records only the ones that conformed to the following criteria (usually used from ITSAK) were digitized:

a) The earthquake which produced the accelerogram must have an equivalent moment magnitude $M_W \geq 5.0$
b) The accelerogram has a peak ground acceleration $PGA \geq 0.05$ g or
c) If the same earthquake triggered another record with peak ground acceleration with $PGA \geq 0.05$g.

The number of records finally digitized and processed with the previous criteria is 420.

Digitization and correction of strong motion data

The first stage of the processing is the digitization. Every record was converted, with an A4 scanner into appropriate (.tif) image files. The choice of the scanning resolution was done after studying the record spectrum for scanning resolutions of 300, 600 and 1200 dpi. The comparison of Fourier spectra for the

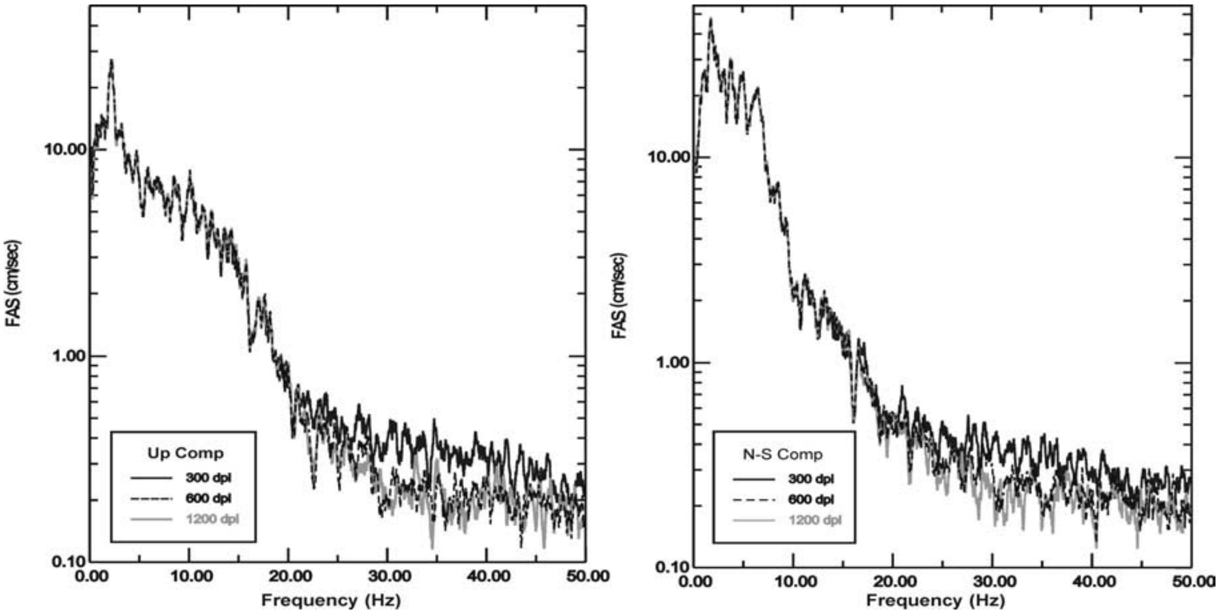

Figure 1. a) Smoothed Fourier Amplitude Spectra of the N-S component of the record Zak18804 scanned with three different scanning resolutions (300, 600, 1200 dpi). b) Same as (a) for the vertical component.

previous scanning resolutions showed that the spectra produced with scanning resolution of 300 dpi were much more 'noisy' than the spectra produced with 600 and 1200 dpi, especially in frequencies larger than 10 Hz (Figure 1). Spectra defined with a scanning resolution of 600 and 1200 dpi are almost identical, which is confirmed by the minimization of the noise due to the high scanning resolution (Figures 1a, 1b). Due to the limitations of the examined analog recording instruments, a maximum recording frequency of about 30 Hz can be observed. Moreover, since a scanning resolution of 1200 dpi would result in very large files, the scanning resolution of 600 dpi was adopted.

In the second stage of the digitization the (.tif) files were converted from raster to vector format using the Kinemetrics Scanview software (KINEMETRICS, 1990). The procedure involves record selection, baseline determination (usually a fixed trace) and correction. The second stage of data processing concerns the generation of the corrected data from the processing of the digitized records. Every digitized record is processed taking into account the recording instrument parameters and uncorrected data are produced, usually referred to as V1 files. The next step is the estimation of the Fast Fourier Transformation for the uncorrected data for frequencies up to 30 Hz. The same procedure was also applied for the two digitized fixed traces, which are two components of the record representing the zero acceleration traces. For the noise study the Fourier Amplitude Spectra (FAS) of the components and the corresponding fixed traces of the record were compared. Since the fixed traces should be equal to zero, any non-zero value and the corresponding spectra is a result of poor recording and digitization errors and will be referred to as noise in subsequent analysis. The record Zak18804 is presented as a typical record in the following figures. It was recorded during the Kyllini (Southwestern Greece) mainshock (**M** = 6.0) in 1984 at an epicentral distance of 20 km and has a PGA value equal to 147.23 cm/s^2 (Figure 2a). The comparison of the Fourier Amplitude Spectra (FAS) of the components and the corresponding fixed traces for the Zak18804 record is shown in Figure 2b.

From Figure 2b it is evident that the seismic signal (continuous line) is higher than fixed trace noise signal (dashed line) only in a certain frequency range. It is also obvious that both spectra show a 'local' variability resulting in a difficulty in the determination of the filtering limits. This variation is the result of the error involved in the application of the Fourier transformation to discrete measured data of continuous functions (e.g. Press et al., 1992). For this reason the Fourier transformations were smoothed as shown in Figure 2c, where the smoothed logarithmic amplitude spectra of every component of the Zak18804 record are plotted.

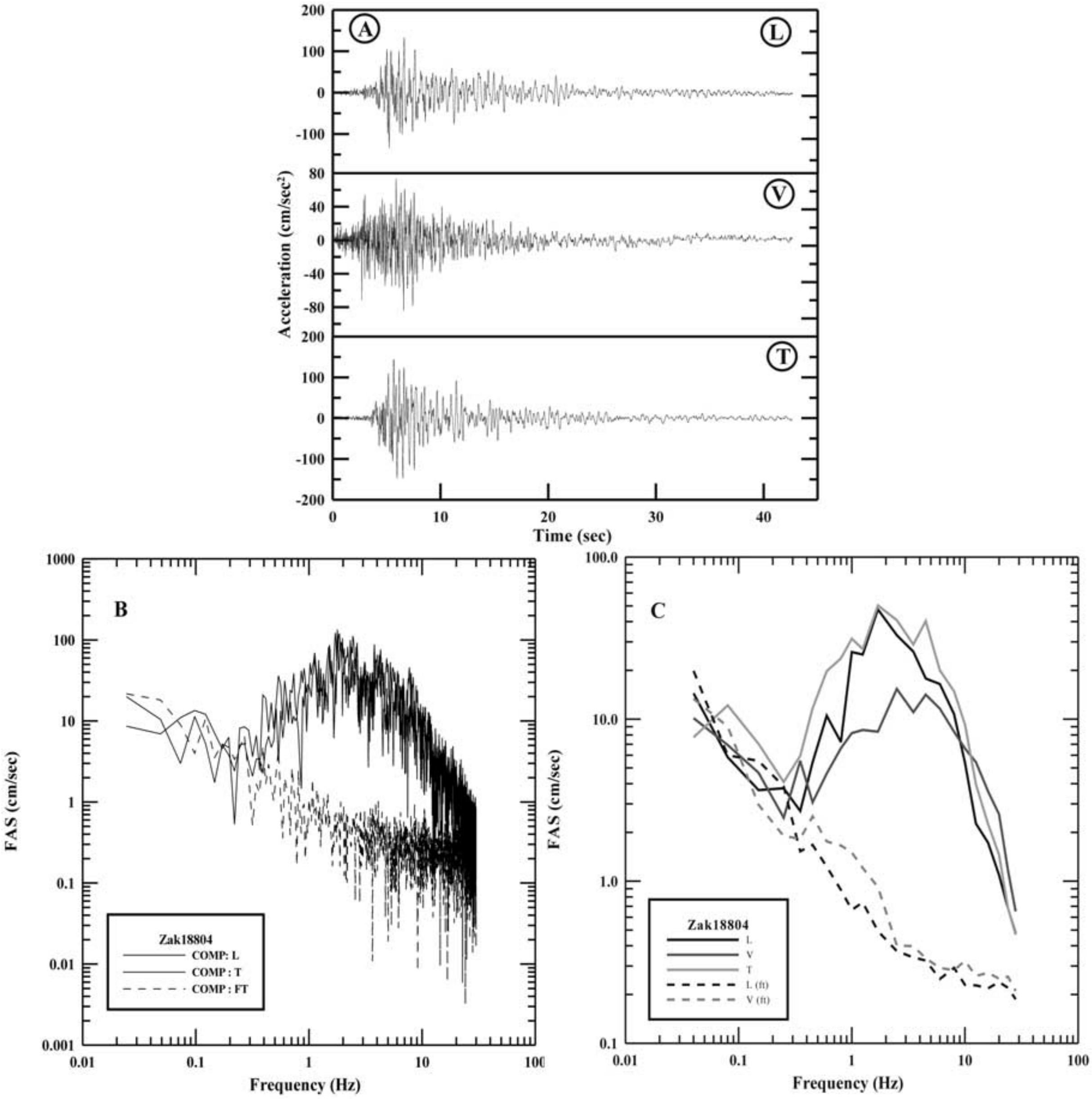

Figure 2. **a)** Time history of the record Zak18804. **b)** Fourier Amplitude Spectra of the horizontal components (L and T) and the fixed trace (FT) of the record Zak18804. **c)** Smoothed amplitude spectra of the components (L, V, T) and the fixed traces (L-FT and T-FT) of the same record.

For the smoothing of the amplitude spectra of the components the procedure described below was followed: The frequency window from 0.05 Hz to 28 Hz was split into 22 sub-windows of equal width in the logarithmic scale and the adopted value was the average value of the amplitude spectrum that lied in each one of these sub-windows.

From the comparison of the spectra of the two horizontal components it is evident that they do not exhibit systematic differences. For this reason in the following processing stages an average spectrum was used for the spectra of the horizontal components. Similarly, the fixed traces spectra were also found, as expected, to be quite similar, hence the average spectrum of the two fixed traces was also used in the following. In

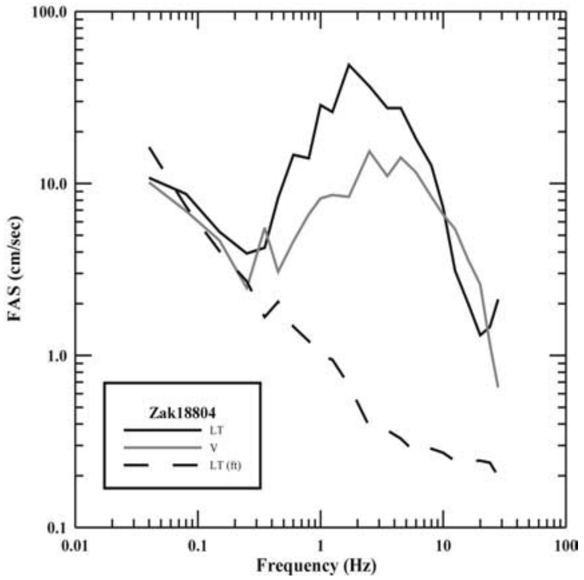

Figure 3. Smoothed mean values of the amplitude spectra of the two horizontal components (L and T), vertical component (V) and fixed traces (LT-FT) of the record Zak18804.

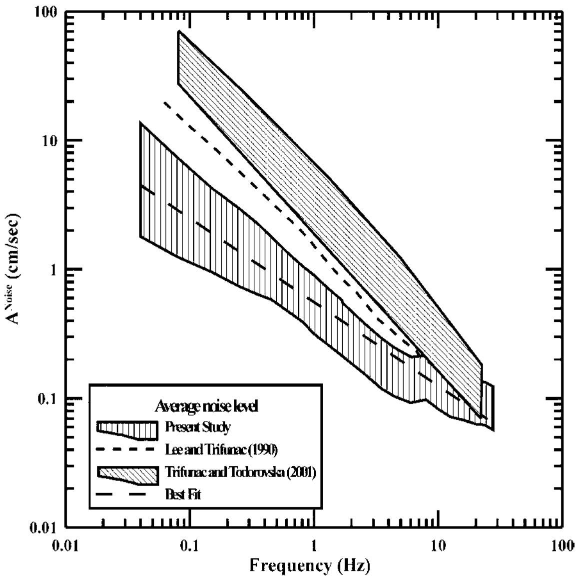

Figure 4. Mean noise curves derived in the present work and comparison with the corresponding curves of Lee and Trifunac (1990) and Trifunac and Todorovska (2001).

Figure 3 the smoothed mean values of the logarithmic amplitude spectra of two horizontal components (L, T), the vertical component (V) and fixed traces (LT-ft) of the record Zak18804 are shown.

The high-pass filters were calculated for every record with the method previously described. For the low-pass filters the characteristic frequencies of 25 and 27 Hz were used for most records in accordance with the frequency response of the recording instrument. This 'rule of thumb' did not apply in some cases where a significant reduction of the high frequency signal amplitude was observed. By applying the previously calculated filters we obtained the corrected data, that are usually referred to as V2 files.

Noise processing

It is reasonable to assume that the recorded noise level for the records which have been processed exhibits similar characteristics. Therefore, it is reasonable to derive an average noise spectrum from all records (Amini et al., 1987; Trifunac and Todorovska, 2001). For this reason we used the data from the smoothed spectra of the fixed traces of all records.

In Figure 4 the average noise level is shown in bi-logarithmic scale. Moreover, the standard deviation, the best linear fit and the corresponding curves produced by Lee and Trifunac (1990) and Trifunac and Todorovska (2001) are also shown. It can be observed that the average noise level roughly follows a linear law with a negative slope. The least squares linear noise curve gives:

$$\log A^{Noise} = -0.65^{*} \log f - 0.25 \qquad (2)$$

that has a linear correlation coefficient r = 0.99 and standard deviation $\sigma = 0.067$.

The comparison of the curve derived from this work with the corresponding curves of Lee and Trifunac (1984, 1990), Trifunac and Todorovska (2001) show that the noise level introduced from the digitization and processing of the records in this work is lower than the corresponding levels derived by the above mentioned authors. This can be partly attributed to the fact that all records used follow the ITSAK's criteria mentioned before, so that the accelerations are less affected from noise level. Also all the records were scanned with a resolution of 600dpi, which is a critical factor for the minimization of noise introduced in the digitization procedure. The importance of the obtained noise curve shown in Figure 4 is clear if we consider that a) Equation 2 was estimated only from the spectral properties of the digitization and processing noise and is independent from the type of the recording instrument and b) a large number of the accelerographs, which are in operation now in Greece, do not record fixed traces and/or time marks, hence the noise level cannot be obtained with the previous procedure. In such cases the comparison with the average noise level determined using ITSAK's strong motion recording network, facilitates the procedure of determining the appropriate frequencies for the filtering of such data.

Calculation of the highpass frequencies as a function of magnitude and distance

The final stage of the processing of the strong motion data is the calculation of equations which associate the cut-off frequency of the high and low filters with the hypocentral distance and the earthquake magnitude. These equations were calculated both for the average spectrum of the two horizontal components, as well as the spectrum of the vertical component of the records.

For the estimation of these equations the following procedure was adopted: After plotting and graphical examination of the data, a linear function of the form $logf_c = aM+blogD+c$, was considered relating the values previously referred. In this function f_c is the cut-off frequency, M is the earthquake magnitude and $D = (\Delta^2 + H^2)^{1/2}$ is the hypocentral distance, where Δ is the epicentral distance and H is the ≪effective≫ depth (mean depth of energy release) of the earthquakes, which was considered constant and equal to 7 km for Greece (Papazachos and Papaioannou, 1997). The calculation of the coefficients a, b and c was performed using least squares'. The linear fit that relates f_c, M and D has been selected after testing different functions, including functions of higher order, with an F-test for the best data fit. The following equations were calculated for the low cut-off frequencies f_c (derived for a signal to noise ratio 2:1) for the horizontal (L and T) and the vertical (V) components.

$$\log f_{C_{LT}} = 0.14115^* \log D - 0.32316^* M + 1.36245 \quad (3)$$
$$\log f_{C_V} = 0.22606^* \log D - 0.32215^* M + 1.39508$$

The root mean square (RMS) error of the cut-off frequencies for the two horizontal and the vertical components (signal to noise ratio 2:1) is $RMS_{f_{C_{LT}}} = 0.238$ and $RMS_{f_{C_V}} = 0.244$ respectively. For the low roll-off frequency f_r (signal to noise ratio 3:1) the corresponding equations estimated are:

$$\log f_{r_{LT}} = 0.14763^* \log D - 0.30083^* M + 1.35360 \quad (4)$$
$$\log f_{r_V} = 0.19943^* \log D - 0.31103^* M + 1.49118$$

The corresponding values for the RMS error are $RMS_{f_{r_{LT}}} = 0.221$ and $RMS_{f_{r_V}} = 0.251$. Examination of equations (3) and (4) easily shows that high cut-off and roll-off frequencies (noisy records) are estimated for earthquakes with small magnitude recorded at large distances, while earthquakes with large magnitudes recorded in small distances have relatively low cut-off frequencies, allowing a larger portion of the spectrum to be studied. This behavior is expected due to the attenuation of the seismic energy with distance and the reduction of the energy released by small earthquakes.

Table 1. Examples of cut-off and roll-off frequencies for the horizontal and vertical components of records produced from earthquakes with different magnitudes recorded in two different epicentral distances

	Horizontal component		*Vertical component*	
	D=10 km	D=50 km	D=10 km	D=50 km
Cut-off (S/N 2:1)				
M = 5.0	0.772 Hz	0.969 Hz	1.024 Hz	1.474 Hz
M = 6.0	0.367 Hz	0.461 Hz	0.488 Hz	0.702 Hz
M = 7.0	0.174 Hz	0.219 Hz	0.232 Hz	0.334 Hz
Roll-off (S/N 3:1)				
M = 5.0	0.993 Hz	1.260 Hz	1.366 Hz	1.883 Hz
M = 6.0	0.497 Hz	0.630 Hz	0.667 Hz	0.920 Hz
M = 7.0	0.249 Hz	0.315 Hz	0.326 Hz	0.450 Hz

It is also interesting to compare the cut-off frequencies of the mean horizontal component of the record with the corresponding vertical component. It is evident that the cut-off frequency of the vertical component shows higher values for the same magnitude and distance, i.e. vertical component is more sensitive to digitization noise than horizontal components. This is expected because of the smaller amplitude of the S waves recorded in the vertical component. Similar conclusions are derived from the comparison of equations (4). In Table 1 examples of the estimated cut-off and roll-of frequencies for the horizontal and vertical components for different earthquake magnitudes and epicentral distances are shown. Because of the large number of data used for the derivation of equations (3) and (4), the estimation of the cut-off frequency from these equations can be considered to be reliable and the obtained results can be used for similar processing purposes.

It is interesting to compare the corner frequency of an earthquake, which is related with the physical properties of the fault (source, fault length) and the high-pass cut-off frequency (equations 3 and 4), which was used for the record filtering and is related with the procedure for removing the digitization noise from a record was made. Such a comparison allows to ex-

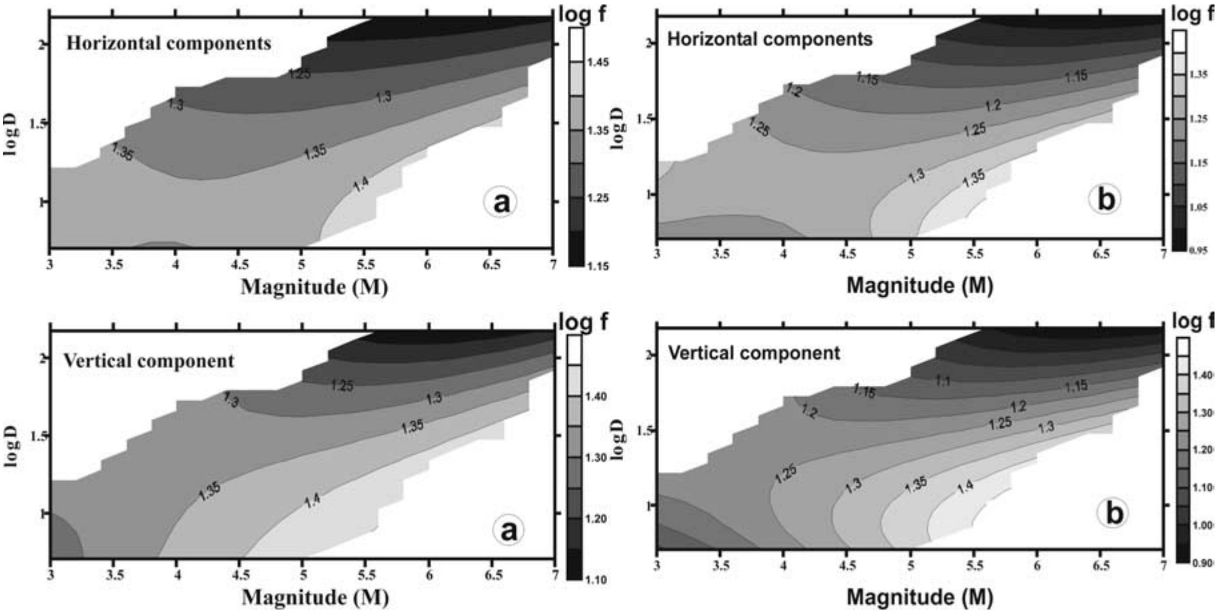

Figure 5. Equal low-pass log-frequency curves for the average horizontal and vertical components, as a function of the logarithm of the hypocentral distance and earthquake magnitude. Log-frequency curves are plotted for signal to noise ratio 2:1 **a)** and 3:1 **b)**.

plore whether the corner frequency of an earthquake is ‘visible’ after the filtering of the digitized analogue acceleration records or not. Comparing equations (3) and (4) with the results of Margaris and Hatzidimitriou (2002) for the corner-frequency of Greek earthquakes suggests that the corner frequency is ‘visible’ only for relatively small-magnitude events ($M \leq 5.0$–5.5), recorded at rather small epicentral distances (0–30 km). Unfortunately, for larger magnitude events ($M > 5.5$) the filtering process ‘masks’ the corner-frequency, even for near-source recordings, due to the relatively low corner frequency of large-magnitude events ($f_c \leq 0.5$ Hz) and the significant noise introduced in this frequency band from the analogue recording and the digitization process. This limitation has to be taken into account when strong-motion data from analogue recordings are used for the study of seismic source properties.

The technique followed for the estimation of the equations of the high-pass cut-of and roll-off frequencies was applied also for the case of the low-pass cut-off and roll-off frequencies. In this case however a linear relation cannot be applied. This is due to the fact that most of the records used in this work have a cut-off frequency larger than 25 Hz, which is imposed by the characteristics of the recording instrument. For this reason curves of equal cut-off frequency were calculated for signal to noise ratio 2:1 and 3:1 for the average spectrum of the two horizontal components, as well as for the vertical one. The corresponding figures are shown in Figures 5a and 5b, respectively. Blanked areas where equal cut-off frequency curves are not shown correspond to regions for which records were not available.

Conclusions

The processing of the Greek strong motion records with the technique adopted in this work can contribute to the solution of several problems related to analog strong motion data processing in Greece. The processing previously described minimizes the average processing time of the analogue acceleration records and the noise introduced from the digitization and processing of the accelerograms. Also a significant result of the homogenous processing of the records is the calculation of mean curve of the spectrum noise for the Greek strong motion records, which constitutes a reliable solution to the calculation of the filtering limits of the accelerograms for which fixed traces or time marks are not available. Appropriate relations are proposed for the calculation of the high-pass cut-off and roll-off frequencies with respect to the earthquake magnitude and the epicentral distance. Moreover, the corresponding equal frequency plots for the low-pass cut-off and roll-off frequencies are also presented. The obtained results suggest that the use of digitized analogue accelerograms for source properties studies should be made with care, due to the reduced frequency extent of the filtered records.

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References

Amini, A., Trifunac, M.D. and Nigbor, R.L., 1987, A note on the noise amplitudes in some strong motion accelerographs, *Soil Dyn. and Earth. Eng.* **6**(3), 180–185.

Basili, M. and Brady, G., 1978, Low frequency filtering and the selection of limits for accelerogram corrections, *Proc. 6th Eur. Conf. on Earthquake Eng.* **1**, pp. 251–258, Dubrovnic, Yugoslavia.

Basili, M., 1987, Data acquisition and processing in strong motion seismology, In: Erdik, M.O. and Toksoz, M.N. (eds.), *Strong Motion Seism.*, Peidel Publ. Company, pp. 251–331.

Crouse, C.B. and Matuchka, T., 1983, Digitization noise and accelerograph pen-offset associated with Japanese accelerograms, *Bull. Seism. Soc. Am.* **73**, 1187–1196.

Hudson, D.E., 1979, *Reading and Interpreting Strong Motion Accelerograms*, EERI, pp. 1–112.

Hung-Chie, C., 1997, Stable baseline correction of digital strong-motion data, *Bull. Seism. Soc. Am.* **87**, 932–944.

KINEMETRICS, 1990, SMA SCANVIEW: *Scanned-based film accelerogram digitization system*, User's Manual, KINEMETRICS/SYSTEMS, Pasadena California, pp. 1–61.

Lee, V.W. and Trifunac, M.D., 1984, *Current Developments in Data Processing of Strong Motion Accelerograms*, Univ. of Southern California, Rept. No **84**(1), pp. 1–99.

Lee, V.W., 1989, Recent developments on data processing of strong motion accelerograms: interpolation of uniform and non-uniform sampling from digitized acceleration data, *Soil Dyn. and Earth. Eng.* **8**, 202–212.

Lee, V.W. and Trifunac, M.D., 1990, *Automatic Digitization and Processing of Accelerograms using PC*, Univ. of Southern California, Rept. No. **90**(2), pp. 1–115.

Margaris, B.N., 1994, New fast digitization and correction procedures of the Greek strong motion records, *XXIV Gen. Ass. Eur. Seism. Com.*, Sept 19–24 1994, Athens, II, 779–786.

Margaris, B.N. and Hatzidimitriou, P.M., 2002, Source spectral scaling and stress release estimates using strong motion records in Greece, *Bull. Seism. Soc. Am.* **92**, 1040–1059.

Papazachos, C. and Papaioannou, Ch., 1997, The macroseismic field of the Balkan area, *J. Seismol.* **1**, 181–201.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., 1992, *Numerical Recipes in FORTRAN, The Art of Scientific Computing*, 2nd edn., Cambridge University Press, 968 pp.

Rinaldis, D., Clemente, P., Pugliese, A. and Sabetta, F., 1994, Low frequency content of Italian strong-motion records, *Proc. 10th Eur. Conf. on Earthquake Engeneering*, Vienna.

Sabetta, F., 1985, Data processing in strong ground motion seismology, *Proc. 2nd Int. Workshop on Stochastic Methods in Structural Mechanics*, pp. 399–420, Pavia, Italy.

Shoja-Taheri, J., 1980, A new assessment of errors from digitization and base line corrections of strong motion accelerograms, *Bull. Seism. Soc. Am.* **70**, 293–303.

Sunder, S.S. and Connor, J.J., 1982. A new procedure for processing strong-motion earthquake signals, *Bull. Seism. Soc. Am.* **72**, 643–661.

Trifunac, M.D. and Lee, V.W., 1974, A note on the Accuracy of Computer Ground Displacements from strong motion accelerograms, *Bull. Seism. Soc. Am.* **64**, 1209–1219.

Trifunac, M.D., Lee, V.W. and Todorovska, M.I., 1999, Common problems in automatic digitization of strong motion accelerograms, *Soil Dyn. and Earth. Eng.* **18**, 519–530.

Trifunac, M.D. and Todorovska, M.I., 2001, A note on the useable dynamic range of accelerographs recording translation, *Soil Dyn. and Earth. Eng.* **21**, 275–286.