ETH Zürich
Institut of Geophysics
CH-8093 Zürich

SS2006

Bachelor Thesis

Using Audification to Distinguish Foreshocks and Aftershocks

David Eberhard

4. August 2006

supervised by
Stefan Wiemer, Florian Dombois and Oliver Brodwolf

1. Abstract

Audification of seismic data uses the circumstance that the ear and the eye have different strength and weakness. This method has never been used in a rigorous scientific research application, and was more considered an educational tool. The main intention of this work is to evaluate the possible uses as a proper scientific application of audification. We used newly developed software to convert seismograms into soundwaves and several people to listen to the earthquakes and verifying audible differences. The software we used in this study was entirely developed for this project and allowed us to do rapid audification of large data amount for the first time.

From the possible objects of study, we selected the distinguishability of foreshocks and aftershocks as our main goal. In addition, we investigated wether or not regions of different earthquake size distribution have different acoustic properties. The distinguishability of foreshocks and aftershocks is a major topic concerning earthquake forecasting, because a more reliable, though probabilistic, identification of foreshocks would be an important step towards time-dependent earthquake hazard assesment. Our hope is to add some fresh information to this old problem.

Contents

2. Introduction

Large earthquakes have frequently caused big destruction, the potential hazard due to large earthquakes has even increased in our time, because of the increased population density in many areas.

The development of a reliable earthquake forecast has therefore become one of the major topics of modern seismology. In these forecasts, foreshocks and their identification are an important factor, as properly identified foreshocks can predict larger earthquakes. The main problem is that even the distinction of foreshocks and aftershocks without the corresponding mainshock is a difficult task to do. Many things have been tried, nothing worked so far(Lin, 2005; Roeloffs, 2000; Bakun and Lindh, 1985; Imoto, 2005).

On the other hand, audification of seismograms never been really tried out in a larger scientific context. Although the chances to find a difference between aftershocks and foreshocks are small, the use of the ears instead of the eyes could be a valuable way to provide fresh insights into this problem.

The main goal of this work is the identification of foreshocks. For this purpose, we suggest two hypotheses, which have to be tested in a proper scientific way and explained in more detail later on:

Thesis I: Foreshocks are distinguishable from aftershocks.

Thesis II: "Extended" foreshocks are distinguishable from "real" foreshocks.

2.1. Foreshock-Aftershock-Multiples

2.1.1. Foreshocks

Clustered smaller earthquake predececing a large earthquake in the same area are called "foreshocks". However there actually two kind of foreshock, the "real" foreshocks which are not really numerous, and something like "extended" foreshocks, which are only called foreshocks because they take place before the large stress drop caused by the mainshock (see figure 1). The size of the temporal and spatial window in which "real" foreshocks occur seems to be not entirely clear, some studies shows that there is a clustering off "real" foreshocks below a epicentral distance of 75 km and in a time window of about 10 days (Reasenberg, 1999). Others pointed out that even beyond an epicentral distance of 10 km, the background activity dominates over the foreshocks (Felzer et al., 2004), and therefore suggested a spatial window of only 10 km and a time window of 2 days. This clustering of earthquakes can actually be used to estimate the probability of potential mainshocks in a region (Imoto, 2005).

However this method is still basic and not very reliable at the moment. The spatial window for the "extended" foreshocks is similar to the spatial window of the "real"foreshocks, but the temporal window can be a lot bigger, as every earthquake between two big earthquake happening in the same region can be called a foreshock.

One of the mainquestions about foreshocks concerning the audification is the question about the physical process underlying the foreshocks phenomenon. Under the proposed theories about origin of foreshocks, there seems to be two which found some agreement: (1) the foreshocks are from the same origin as the aftershocks, triggered by a stress

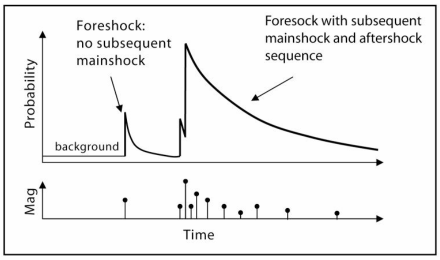


Figure 1: Schematic of foreshocks, mainshock and aftershocks. (Picture: USGS)

change (Felzer et al., 2004) (2) the foreshocks are triggered by the nucleation phase of a upcoming larger earthquake (Ohnaka, 1993; Dodge et al., 1995; Hurukawa, 1998).

The relationship between the foreshocks and the corresponding mainshock is another point which we should mention. A correlation between the foreshock magnitude, the mainshock magnitude, between the area on which the foreshocks are scattered, and the magnitude of the mainshock does not seem to exist. Neither does there seem to be a correlation between the numbers of foreshocks and the magnitude of the mainshock (Felzer et al., 2004). This means that the mainshock is "announced", but not really determined by the foreshocks.

The rate at which the foreshocks occur before a certain large earthquake depends on the local tectonic and the focal mechanism(Reasenberg, 1999). The foreshock rate can be estimated with the empirical relation (Felzer et al., 2004):

$$foreshockrate = 0.134 * aftershockrate$$

This relation is calculated with a single triggering model in mind.

2.1.2. Aftershocks

Aftershocks are clustered earthquakes that follow a larger one in the same area. The larger earthquake can be the mainshock, in which case the aftershocks are called "primary aftershocks", or it can be an aftershock too, in which case the following aftershocks would be called "secondary aftershocks'. It has been shown that a group of small aftershocks can also trigger secondary aftershocks (Felzer et al., 2003). The fraction of aftershocks that are secondary do increase with increasing time and increasing magnitude of mainshock. The secondary aftershocks and their variations have been shown to be very important for the aftershock forecasting after large earthquakes.

How far away from the mainshock an aftershocks can occur is variable. Normally the area in which aftershocks are about to occur is estimated as about one-time to two-times the length of the mainshock rupture, but recent studies suggested that dynamic stress can trigger aftershocks much further away. This process is called "remote triggering" (Ziv, 2006). The time window in which the aftershocks occur is controlled by a decay rate and can be modelled by the modified Omori Law (Utsu, 1961):

$$R = A(t + c)^{-p}$$

where R is the aftershock rate, t is the time and A, p and c are constants. The constant p is typically in the range of 0.7 - 1.5. This relationship fits the aftershock sequence well for near aftershocks, but for remote aftershock triggering, this is not always the case.

The question about the physical process behind the aftershocks seem less contraversal as for the foreshocks. There is general agreement that stress changes (either dynamic or static) induced by the mainshock play a major role. As we mention before, it has been pointed out that the underlying process for the foreshocks and aftershocks could be the same, which could be important concerning the distinguishability of foreshocks and aftershocks. Besides this plausible relation between foreshock aftershock we have to keep in mind that there are many more aftershock in the larger area than foreshocks, which cannot even be identifed in greater distance from mainshock's epicentre. Another difference between the two is that the aftershock production rate depends on the mainshock magnitude, so there is a clear relation between mainshock and aftershock.

As big earthquakes can produce very large, potential harmful earthquakes, knowledge about potential aftershock regions is of high public interest. So called "probabilistic aftershock hazard"or short "PAH"maps are used to portray the probability of aftershocks. This maps can be calculated at almost realtime just after 4 days (Wiemer et al., 2002; Gerstenberger et al., 2003).

2.1.3. Multiples

Multiples (or doublets) are something like large aftershocks, and there are actually strong arguments that they have the same physical origin and therefore are really just large aftershocks. Multiples are not as common as they normal aftershocks, the rate with which the occur is estimated by (Felzer et al., 2004):

$$doublerate = 0.28 * afterhockerate$$

However, multiples are not studied here in any detail.

2.2. b-values

The relativ occurrence of earthquakes within a certain magnitude can be described by a power-law, the Gutenberg-Richter equation (Gutenberg and Richter, 1944):

$$logN = a - bM$$

where N is the cumulative number of earthquakes with a magnitude ≧ M, and a and b are constants. The constant a represents the productivity of a certain volume, whereas the constant b is the frequency-magnitude distribution. The actual meaning of this b-value can easily be imagined, as the b-value is the slope of the frequency-magnitude distribution. A small b-value means a flatter curve and relatively more large earthquakes. The b-value is generally used to forecast the frequency of large event from the occurrnce of small ones, thus important for hazard relevant studies.

The b-values are not constant, they vary in time and space. However, the spatial variation is much stronger and more remarkable(Wiemer and Wyss, 2002). The variation with time is less pronounced and also not as easy to detect, since most temporal variations are more due to changes in the network configuration rather than due to natural sources (Schorlemmer et al., 2004). Nevertheless, larger earthquakes will induce changes in the b-values, and as we listen to foreshocks and aftershocks, the b-value change because of the mainshock can possibly be heard. The potential effect of the b-value on the sound will not be covered in this work.

2.3. Why Listen?

The question is actually misleading, we should more ask why *not* listen? Although the ear has been used successfully in the scientific past, the eye is today the dominant sense in science as probably in the most other matters as well (Dombois, 2002b). This incident is suprising and not: suprising as we all know that the world we experience, whether it is with the eyes, ears or any other sense, is only an image of the real world, which could have nothing to do with the real world. One of the main reasons for the dominance of the eye could be the properties of the eye, which differ from the properties of the ear. Another reason could be that visual information is much easier to store and to reproduce, and it has been done earlier in the past, if we think of written documents and drawings. Reproduction of audio information on the other hand is much more complicated and has only in the recent past become technically feasible.

So what are the propeties of the eyes, what makes them so different from the ears, or what are the strengs of eye and what are the strengs of the ear?

Properties of the eye:

- Frequency range from 385 THz to 790 THz, which is about one octave.
- The eye is a directional and focused sense and is as such very strong in seeing the world in a static way.
- The eye is on the other hand not very good at experiencing the time, which can be a benefit if thinking about television, or a disadvantages.
- The eye is a very unaffecting sense, we can only "scratch"the surface of an object, but never look inside an object.

Properties of the ear:

- Frequency range from 16 Hz to 20 kHz, which is about 10 octaves.
- The ear is an unidirectional and unfocused sense, it does not even differ between sound from inside the body or outside the body.
- Unlike the eye, the ear is very strong at sensing time, this ability goes even so far, that the ear ist incapable of recognising a sound without time. There is nothing like a freeze image in the audio domain.
- Under certain conditions the ear can hear inside an object.
- The ear is strong at filtering certain signals out of the surrounding noise, which is also called the "cocktailparty effect".

As we see above the eye and the ear have quite different properties, which is the main reason why we should also try the ear instead of the eye for addressing scientific challenges.

2.4. What Can We Hear?

We do not really know what we will hear, that's the very reason why we do this study. However, there has been some earlier studies which have shown some potential (Dombois, 2001). Several factors have been heard[1] in these studies:

Distance: The sound change with greater distance, which easily can be explaned by the dispersion of the waves and of course other factors. It could even be heard if a wave traveled through the core .

Region: The earthquakes of a certain region showed some similarities in sound.

Depth: Depth does not seems to have a strong influence on sound, what probably can be explained by relatively small depth variation. An interesting case are

[1] Sound examples to some of the mentioned factors can be heard on the DVD or on the Internet under the adress: http://www.auditory-seismology.org

for example deep earthquakes (up to 670 km) which exhibit a very special sound (Dombois, 2002a).

Site Response: As for the earthquake regions, the region on which the seismometer stands has an influence on the sound. This fact has to be taken in account when listening to earthquakes.

Noise: The background noise of seismic stations is another characteristic which can be heard. Analysing the audification of the background could be another interesting subject of future studies, as an audifiction of the background noise can help to get a better understanding about the underground and of artefacts and noise sources.

Tectonics: Not really a surprise, the focal mechanisms has an influence on the sound. The sound of a mid ocean rift for example is described as a plop like sound, where as the subductions zones sounded more like some hard cracks and clicks (Dombois, 2001).

Free Oscillations: The largest earthquakes can bring the entire earth to resonate in her eigenfrequencies. The eigenfrequency are a property depended on the structure of an object, in this case of the earth. These Free Oscillations can be easily heard (Dombois, 2002a).

People tried to listen to some synthetic seismograms, but they sounded not very convincing (Scherbaum, personel communication, 2006). This suggests that the model generating this artificial seismograms is not good enough and can be improved. The audifiction of seismic waveforms could potentially be a way to a better understanding about the earthquake generation.

3. Data

As training datasets we need a large number of foreshock and aftershock data. For this reason, we have chosen two large mainshocks and their corresponding foreshock and aftershock sequences. The two mainshocks we selected are the Landers earthquake 1992 in California and the Hector Mine Earthquake 1999 also in California(Dodge et al., 1995; Wiemer et al., 2002). Why we have taken these two earthquakes is fairly simple, as a look on properties of the two easily shows. They are similar in their magnitude and took place on the same location(Wiemer et al., 2002). Also, the region of California has a good network coverage and is well studied.

If we look closely at the distribution of earthquakes with time and space, we see clearly that the earthquakes are scattered around the faults in this region. We also see that in a smaller region around the mainshocks, the aftersocks dominate over the foreshocks (see figure 2). A pattern which is also visible if we look at the cumulative earthquake plot (see figure 3). Note that the Mw 6.1 Joshua Tree earthquake 3 months before the Landers earthquake is not from the same fault, so it is not an actual foreshock.

As we mentioned before, the b-values can be something we can potentially hear, so we should also look at the b-values of the two mainshocks and their foreshock-aftershock sequence. The b-value map (see figure 4) for the Landers and the Hector Mine sequence seems to differ a bit from each other. However, both seem to have spatial variation of the b-values around the mainshock area.

3.1. The Earthquakes

The whole catalog of earthquakes for the certain periods would not be very manageable,

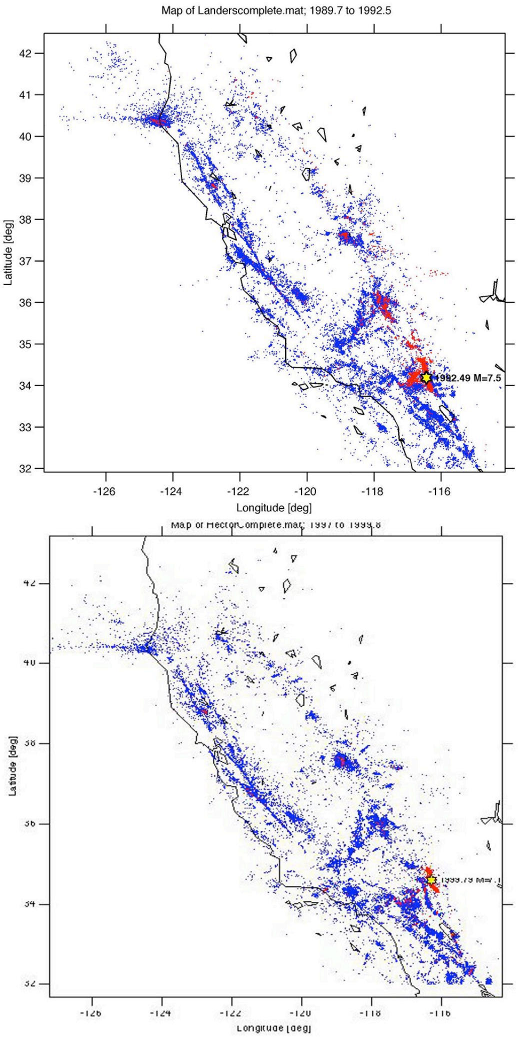


Figure 2: a) The map shows every earthquake 1000 days before and 10 after the Landers earthquake which is marked with a star. b) The same for the Hector Mine earthquake. The blue points are earthquakes which have taken place before the corresponding mainshock and the red points are earthquakes after the mainshock

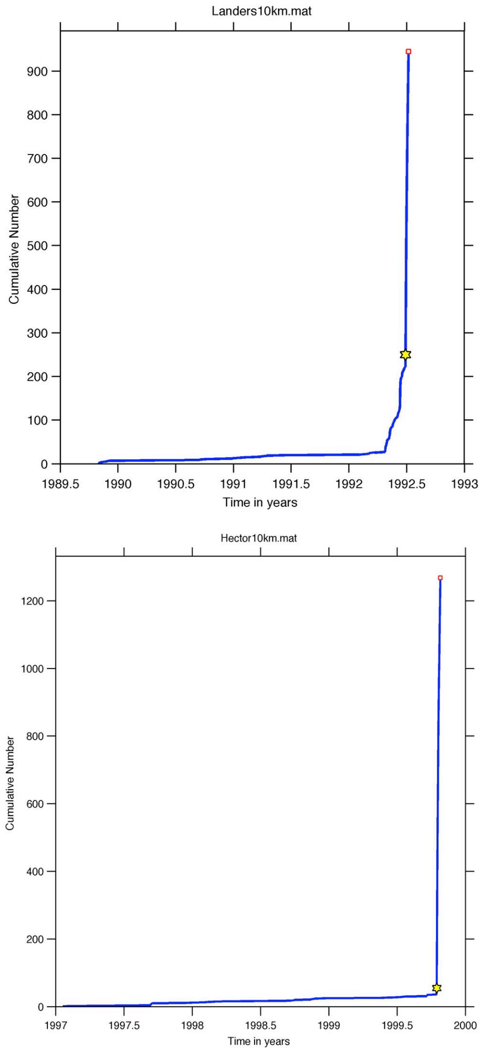


Figure 3: The cumulative number of earthquakes with time plot, a) the Landers earthquake, b) the Hector Mine.

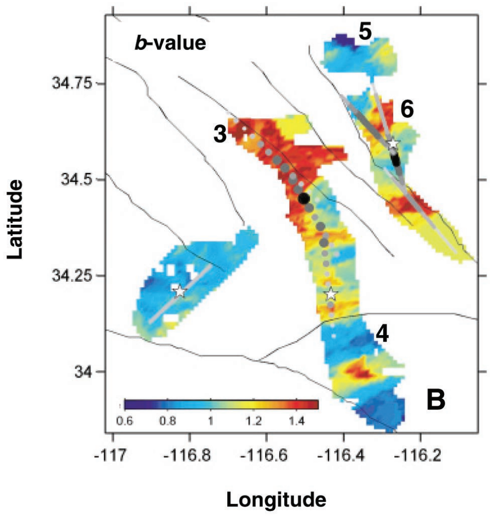


Figure 4: The b-value map of the Landers-Hector Mine region based on the period of 3-600 days after the Landers and the Hector Mine mainshocks(Wiemer et al., 2002)

as there would be a large number of earthquakes we would have listen to. Neither would it make any sense, as we would hear to many other factors. We have to choose some selection criteria to obtain a more manageable dataset and to minimize unwanted factors, such as differences in the sound due to other faults.

For Thesis I we selected earthquakes up to 1000 days before the mainshock. Aftershocks, which are quite numerous, were selected up to 10 days after the mainshocks. With 1000 days before the mainshocks as first temporal border we have no only the ”real“ foreshocks but also a lot of earthquake, which are not foreshocks in the selection, but as we in a first step only want to hear a difference before and after the stress drop, there is no problem in that selection.

For the spatial selection of the data for Thesis I, we have chosen events within 10 km of the epicenter. With this selection we will not get to much background seismicity in the foreshocks and we will cut down the number of aftershocks, which is a good thing as we have to enough of them anyway. An other reason why we have choosen the 10 km is that with this selection the location of the sources do not vary to much and, hopefully, changes of the sound due to the different raypaths of the earthquakes also.

For Thesis II we strive to distinguish between foreshocks and other earthquake before the mainshock. We differentiate the 1000 days before the mainshock further by an adequate temporal and spatial window. This window can easily be found in a time versus distance plot (see figure 5). In our case the foreshocks of the Landers earthquake are defined as earthquakes with a epicentral distance smaller than 1 km and in a temporal window between 1992.25 and 1992.5. For the Hector Mine earthquake they are defined as within an epicentral distance of 1 km and a temporal window between 1999.5 and 1999.8. With this selection criterias we have a total number of 19 ”real“ foreshocks for Landers mainshock and a total number of 11 ”real“foreshocks for the Hector Mine earthquake.

For both Theses, there is also a selection of the magnitude, as comparing the sound of a magnitude M_w 5 earthquake with a M_w 2.5 earthquake would be as wise as comparing the sound of hardly blown flute with that of an overblown flute. Therefore, we only selected earthquakes with magnitudes between M_w 1.5 and M_w 2.5. This also has the advantage that we cut down the number of aftershocks once again.

The catalog we used for the selection was a combined catalog of data from the Northern California Earthquake Data Center and data from the Southern California Earthquake Data Center. The number of remaining events can be seen in Table 1.

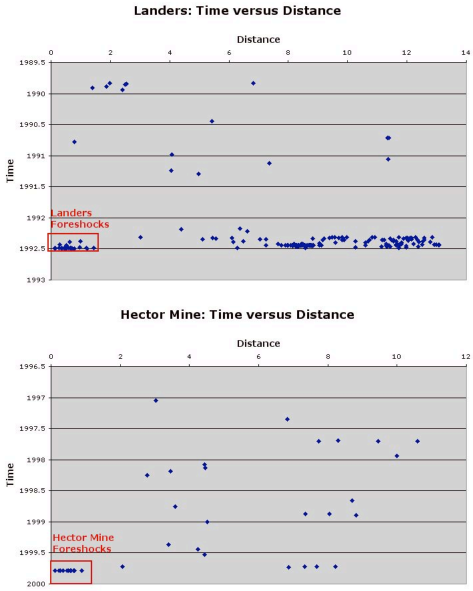


Figure 5: The distribution of earthquakes in time and distance before a) Landers and b) Hector Mine earthquake. Note the numerous "foreshocks" before the Landers mainshocks. These foreshocks could also be aftershocks of the Joshua Tree mainshock.

	Landers	**Hector Mine**
Total Number	541	843
"Extended" Foreshocks	150	25
"real" Foreshocks	19	11
Aftershocks	372	807
Total Number of Waveforms	5446	10482

Table 1: A compilation of the quantities of the different events. Note that the these numbers are the total number of events, consisting of the trainings set and the testing set.

3.2. The Stations

After the catalog selection we now select waveform records from stations. The perfect selection of station would be **one** set of stations for both mainshocks with the best possible channel in terms of sampling frequency and dynamic resolution and of course every earthquake recorded on every station of the set and, if possible, continously recorded. However, nothing is perfect and so is this selection. One of the biggest problems is actually to find stations that have been online for the whole period of foreshocks, mainshock and aftershocks and with the same channel, as comparing sounds of different channels would not be sensible. To get a useful set of stations for the two mainshocks, we have to select a set for each mainshock. The price for the better selection is that we cannot always compare foreshocks and aftershocks between the two mainshocks. Another problem is that the earthquakes are very small, so not every earthquake gets registered by every station. Nevertheless, there were enough waveforms left for each station.

The actual station selection consist of 16 stations for each of the mainshocks and there corresponding foreshocks and aftershocks (see tables 2. and 3. and figure 6). The selection criterials are as following:

- Every station between 116°W and 117°W and between 34°N and 35°N, defined as "near".
- Some stations between 115°W and 118°W and between 33°N and 36°N, defined as "extended'.
- Only the triggered EHZ channel was selected.

There are two reasons for this "extended" selection, first we wanted to have enough data and enough stations, and there simply were

Shortname	Longitude	Latitude
RAY	-116.81306	34.03749
MLL	-116.93713	34.09125
TPC	-116.04939	34.10564
CPM	-116.19771	34.15442
RMR	-116.5763	34.21283
SIL	-116.82746	34.34802
LUC	-116.96474	34.45476
NW2	-115.69266	33.08732
ORK	-115.76994	33.56623
DTP	-117.84581	35.26742
CH2	-115.33693	33.29624
TOW	-117.76493	35.80885
BLK	-117.21975	35.08867
LRM	-117.69	35.47737
VST	-117.232	33.15585
WSC	-117.88751	35.70429

Table 2: Station selection for the Landers earthquake.

not more stations in the near region, and secondly earthquakes to a further away station probably have a more homogenoues raypath than to nearer stations.

The selected EHZ channel is a triggered high gain channel with a sampling frequency of 100 Hz. The reason for the EH_ selection is very simple as it was the best most commonly available channel at this time and region. As for the component orientation we followed the suggestions of Florian Dombois (Dombois, 2002a) and choosen the vertical component. However, the use of the other components could be subject of future studies.

4. Method

The method to distinguish foreshocks and aftershocks using the ear instead of the eyes can be separated in two steps, the pure audification and the process of listening.

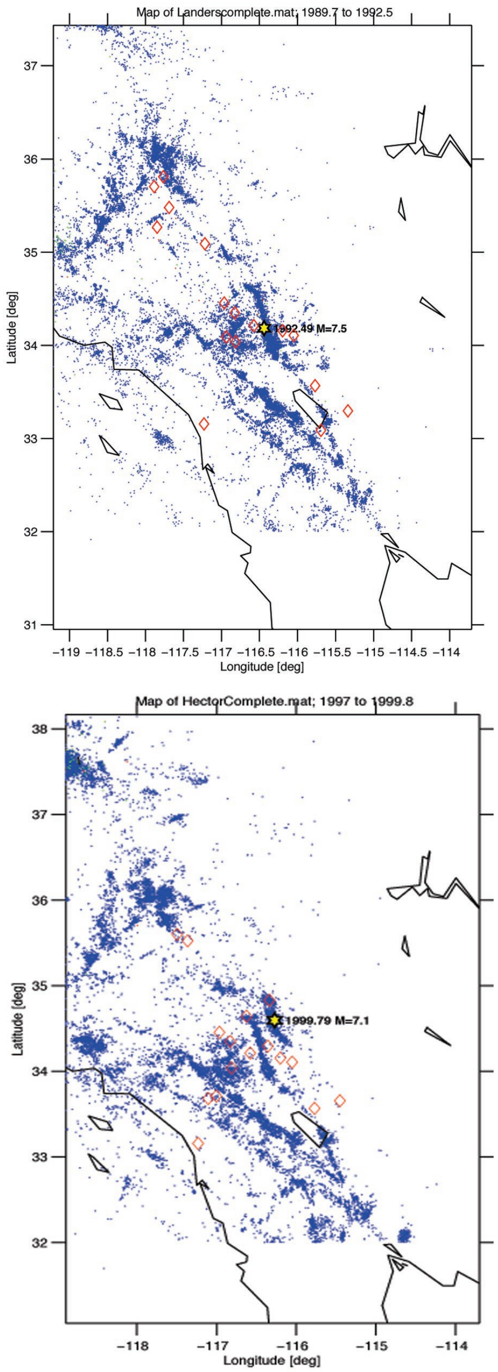


Figure 6: Map of the selected station for a) the Landers and b) the Hector Mine earthquake.

Shortname	Longitude	Latitude
RAY	-116.81306	34.03749
TPC	-116.04939	34.10564
CPM	-116.19771	34.15442
RMR	-116.5763	34.21283
GTM	-116.356	34.2946
SIL	-116.82746	34.34802
LUC	-116.96474	34.45476
RMM	-116.62438	34.64384
CDY	-116.33717	34.83007
VST	-117.232	33.15585
ORK	-115.76994	33.56623
XMS	-117.36418	35.52314
WIN	-117.10366	33.68299
BC3	-115.45309	33.65484
WSH	-117.49265	35.59962
HMT	-117.00392	33.70883

Table 3: Station selection for the Hector Mine earthquake.

4.1. Audification

Beside the parameter mapping[2], which will not be topic of this study, there are several ways to convert a seismic waveform into a audio waveform. Each of them has advantages and disadvantages. The main problem in the audifiction of an earthquake is the difference in the property of a seismic wave compared with a sound wave (see table 4). Especially the frequency spectrum differs a lot, the spectrum of a seismic wave ranges from 0.3 mHz to 20 Hz, whereas the hearable sound wave has a spectrum of 16 Hz to 20 kHz. Written in more demonstrative way: 17 octave of the seismic against 10 octave of the sound wave (Dombois, 2001).

The simplest way to get a sound out of a seismogram would be a linear time compression, which is a simple speed-up of the signal, very similar to a speed-up of a vinyl record. The advantages of such a simple procedure are first of all the simplicity of the method itself and the fact that with this method the inter-frequency spacing and the signal's characteristics are conserved. The disadvantages of this procedure is the loss of information due the non-audible part of the 17 octaves, which cannot be fit into the frequency spectrum of an audible signal. The signal also get's shorter, which is most of the a time an advantage, but not necessarily always.

[2] In this method the actual data or waveform is mapped to parameter of soundgenerator as a synthesizer, the result depends strongly on the chosen soundgenerator. This kind of method is often referred to as sonification

	seismic wave	acoustic wave
frequency	0.3 mHz-20 Hz	16 Hz-20000 Hz
octaves	17	10
word size	24-32 bit	16-24 bit
dimensions	3	1

Table 4: A comparison of the properties of a seismic wave and the properties of an acoustic wave.

Another way to get an audible signal is to raise the frequency linearly, which is also called a pitchshifter. The advantages in this case would be the unchanged inter-frequency spacing and a controllable length of the signal. However, such a method would either use a fourier transformation, a granular stretch method or the doppler effect as soundprocessor sometimes does, and this could result in artefacts and alteration of the signal. The problem of information loss due to the frequency is also not solved.

A more sophisticated method would be a non-linear time compression. With such a method, the 17 octaves of the seismic wave could be fitted into the frequency range of the sound wave, which is a clear advantage. However, this method would be more complicated and the result would much more depend on the actual choice of the speed-up function. In this method the inter-frequency spacing and so the signal characteristics would not be conserved.

Today most of the seismograms are recorded with word size of 24 bit or even 32 bit. Ironically the A/D converter with such a word size are originated in professional audio recording. However many consumer audio players (e. g. CD-players) only have a word size of 16 bit. Although these things change and 24 bit audio player as DVD-players or many computer soundcards are these days not that uncommon, a word size reduction from 24 bit to 16 bit has to be considered. The loss of such a reduction would be the loss of accuracy per sample and with that a degradation of the signal-to-noise ratio. How strong the effect of the word size reduction really is has to be surveyed in other studies.

For this study we followed the suggestion of Florian Dombois and used the linear time compression method. For the speed-up factors we use variable factors, which means the final sampling frequency is 44100 kHz resulting in a speed-up factor of around 441 (Dombois, 2002a, 2001). The converter software can additionaly slow down the playback time of the waveforms if desired, we used this to double the playlength of earthquakes. We also applied a damping factor of 2100 in order to avoid distortion in the resulting audio waveforms[3] . Out of compatibility reason, we applied a word size reduction from 24 bit to 16 bit, so we can use most of the available soundplayers.

After the audification, we stacked the resulting soundfiles in correct temporal order into longer sequences of foreshocks and aftershocks for every station. This has to be done to get a more convenient soundfile, as listening to individual earthquake would have been too time consuming. See figure 7 for a schematic view of the whole process.

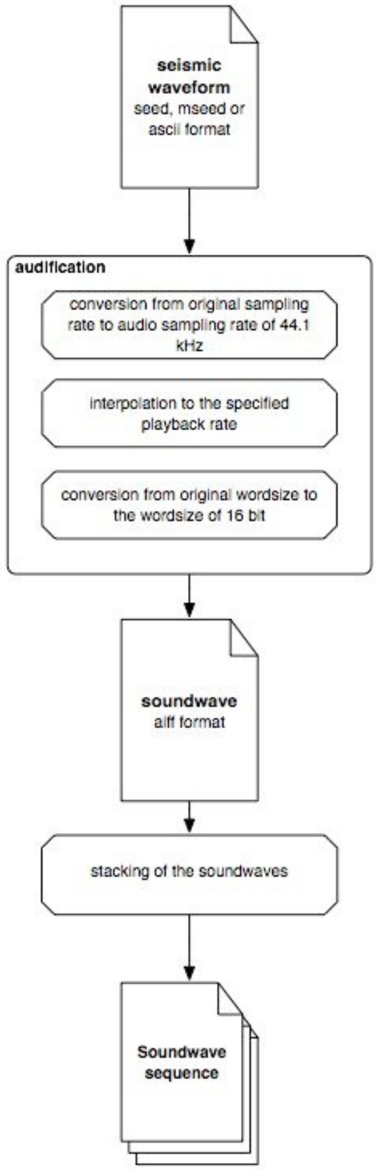


Figure 7: Schematic of the whole processing

[3]see Appendix for a manual of the converter software

4.2. Listening

There is more then one way to listen to the seismograms. The simplest and most obvious method is to listen to each seismogram alone and try to distinguish them. Of course this has to be done for a particular station, as the location and properties of a station affects the sound.

An other way is to listen to more than one station at the time, this would involve more then one speaker (see figure 8) or more complicated 3D sound processing. Although this method is more complicated and extensive, there is also more information to gain and the listening process could be faster.

In both methods, filters and other sound effects like compressors and reverberation effect can be used in order to modify the sound in a certain way.

It is essential that more then one person listens to the data, because only if the difference is heard by several persons we can assume that the difference is real. It is also desirable to involve people with a musical education, in our case from the Y Bern[4]. It is also essential to split the data into a "training-set", as it says for hear training purpose, and into a "test-set', which is necessary to verify the heard differences in a double-blind study.

In a first step, we will use the simpler quake by quake method and probably later on try also the more sophisticated multistation method.

[4]Institute for Transdisciplinarity of Berne University of the Arts

Figure 8: The 19 Speaker Surround System of the Y Bern

5. Results

After repeating the entire processing chain outline in chapter IV for all the available event, we finally obtain 32 sequences of foreshocks and aftershocks for both datasets (see table 1 for the numbers of events). These can be listened to on the DVD enclosed with this thesis (see in the Appendix for an index of the DVD).

The sound of single earthquake can generally be described as a small "click" sound (Bsp. 3032480.CI.TOW.EHZ.aif in the Landers sequence, see also figure 9) for the earthquakes with a small magnitude and as a louder and deeper "rumbling"sound (Bsp. 12179059.CI.TOW.EHZ.aif in the Landers sequence, see also figure 10) for the earthquakes with a larger magnitude. Some earthquakes also seems to have small echoes in the sound (Bsp. 2056929.CI.MLL.EHZ.aif in the Landers sequence, see also figure 11).

Looking at the entire dataset there are some properties in the sound, that are not surprising as they have been heard before(Dombois, 2002a, 2001):

Station-effect: The effect of the background noise that every station has can be well

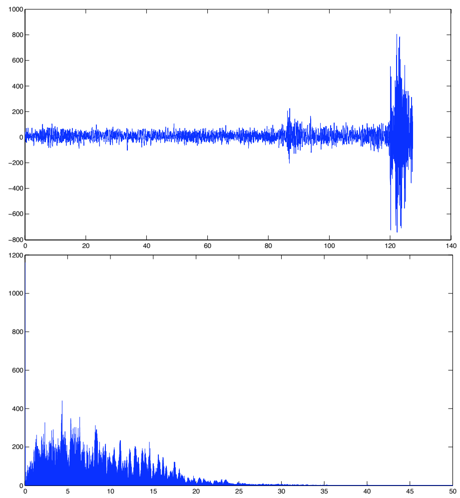


Figure 9: The seismogram (a) and the FFT of event 3032480. This event sounds like the descripted small ”clicks“. The event can be listened to on the DVD.

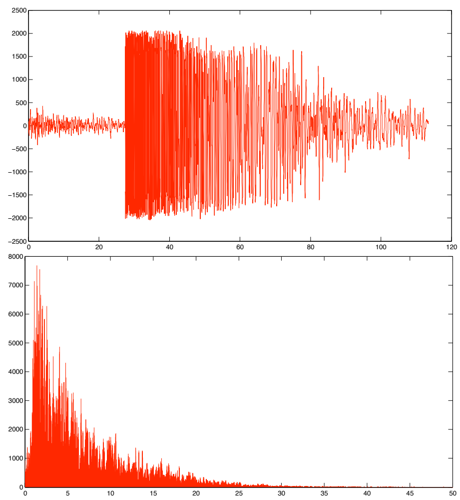


Figure 10: The seismogram (a) and the FFT of event 12179059. This event sounds like the the descripted deep ”rumble“. The event can be listened to on the DVD.

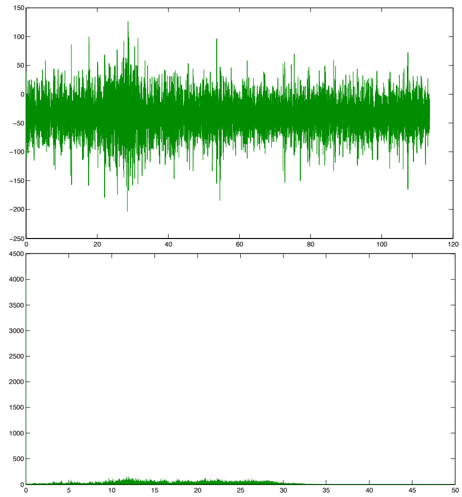


Figure 11: The seismogram (a) and the FFT of event 2056929. In this event the descripted echo can be heard. Note also that this event is one of the mentioned ”special sounding“ foreshocks.

heard over the whole time, and every station gives it distinct ”colour“ to the sound. The effect of the station is hard to see in the corrensponding seismogram (see figure 12). This differences can be better seen in the amplitude spectrum of the waveforms (see figure 13). However, the differences in the amplitude spectrum are not so demonstrative as the audifaction of the waveform is.

Remarkable is that although the original seismograms are triggered and not continuous signals, the background noise does sound continuous. There also seems to be something like ”normal“noise typical for every station and some sort of variations of it, which can be heard in some time periods.

Distance-effect: The effect of the epicentral distance can be noticed in the sound itself, as the more distanced earthquakes produce much quieter and homogeneous

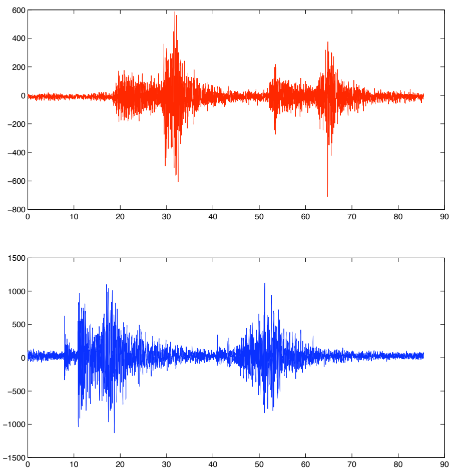


Figure 12: The seismogram of the same event (3032890) in the Landers sequence for two differnt stations: a) The ORK station, b) The RAY station. The differences of the noise can be hardly seen in the seismograms, but it can be well heard. Both audio files can be found on the DVD.

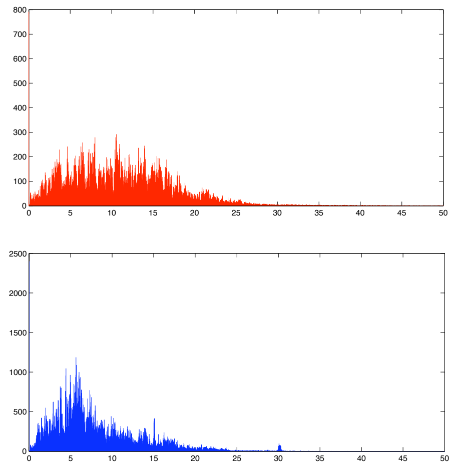


Figure 13: The amplitude spectrum of the same event (3032890) in the Landers sequence for two differnt stations: a) The ORK station, b) The RAY station. The differences of the noise can be better seen in the spectrum than in the wavefom. However, listening to the waveforms is more demostrative than examining the spectrum of the event. Note the small peak around 30 Hz in the spectrum of the RAY station, this feature can be easily heard in the audification. Both audio files can be found on the DVD.

sounds. The distance can also be noticed in the number of earthquakes we have for each station, station more distant have less registered earthquakes as stations nearby the mainshock.

Region-effect: As suspected the effect of the earthquake region is not well heard in this dataset, only some of the more ”special“sounding earthquakes could be due to regional effects. The region effect can be neglected.

5.1. Landers

Probably due to the Joshua Tree earthquake, we have a relatively large number of earthquakes before the Landers earthquake, which makes this dataset a good choice for testing Thesis II. However, a difference between foreshocks and other earthquakes could not be identified so far. The only exception are some foreshocks which sounded bit "stronger" than the other earthquakes.

As expected, we have a much larger number of aftershocks, due to a relatively long aftershock sequence. Right after the mainshock, the earthquakes sounded generally "stronger" and "darker" as before the mainshock, there was also some sort of high-frequency crackle in this sound, which could be secondary small aftershocks. This effects can be heard on all stations except some stations further away, on which the sound got changed to rumble because of the distance.

After 240 earthquakes in the aftershock sequence the louder and stronger sounding earthquakes begin to disappear and the quieter and smaller sounding earthquakes and the background noise dominates again. At this position the sequence of earthquakes before the mainshock and the aftershock sequence cannot be distinguished clearly. This effect can be heard in the sequence Landers-BLKpost.m4a (see DVD) after about 49 seconds.

5.2. Hector Mine

Unlike the Landers earthquake, we do not have many earthquakes before the Hector Mine mainshock. This results in a much shorter audio sequence, which is not very usefully concerning Thesis II. This sequence also misses the louder foreshock we have heard in the Landers sequence.

The Hector Mine aftershock sequence is even longer than the Landers aftershock sequence. Similar to the Landers aftershock sequence the first 22 aftershocks are very strong and dark sounding and with the same crackle (see the first 10 seconds of the sequence Hector-CDYpost.m4a on the DVD as example). In some stations near the Hector Mine epicenter, the aftershocks were so loud that we even had problems with distortion in the sound, forcing us to use the before mentioned damping factor in the conversion software. The same decay of louder earthquakes we have heard in the Landers aftershock sequence can be heard in the Hector Mine aftershock sequence, only the decay seems to be even stronger and the sound of the aftershock sequence returns faster to the sound before mainshock. This effect can be heard after 166 aftershocks, compared to the overall length of the aftershock sequence of 807 events this is less than in the Landers mainshock. The effect can be heard on the DVD in the sequence HectorCDYpost.m4a after 42 seconds.

Generally, the sound of the Landers and the Hector Mine earthquakes are quite similar. Also the station background noise of stations we used in both cases was very similar.

6. Discussions

Besides the known hearable factors, there are two effects that could be heard:

- The louder and stronger foreshocks in the earthquake sequence before the Landers mainshock.
- The stronger sounding aftershock right after the mainshock
- The decay of the stronger sounding aftershocks

The question is where those effects in the sound come from. They could originate in a change of the stressfield, which would justify Thesis I and Thesis II. They also could be due to some other effects. In order to justify any hypothese we have to exclude all other effects than can be heard.

6.1. Magnitudes

Differences in the earthquake magnitude would result in differences in the sound. The magnitude has been limited to between M_w 1.5 and M_w 2.5 within the selection of the earthquakes, but this does not mean that there could be no bias in the magnitude.

To analyse the magnitude changes in the Landers and in the Hector Mine sequences, we plotted the magnitudes of the single earthquakes and a sliding mean value of order 10 against the position in the sequence (see figure 14 and 15). The position in the sequence is similar to the time, but has the advantage of a better readability. We see that for the Landers sequence there is a jump in the magnitude right after the mainshock. An even stronger jump in magnitude can be noticed in the Hector Mine sequence. This probably explains the differences in the sound right after the mainshock as well as the problems with distortion we had in the Hector Mine case. An explanation for this jump in the magnitude could be a change in the magnitude of completenes M_c (Woessner and Wiemer, 2005).

Also we see some sort of decay of the sliding mean value of the magnitude in the Hector Mine aftershock sequence and, less pronounced in the Landers case. This could be a good explanation for the decay of the stronger sounding earthquakes we have heard, and it also explains the faster decay in the Hector Mine case. For the Landers case we also have to keep in mind that the aftershocks are less numerous and so the sequence is shorter.

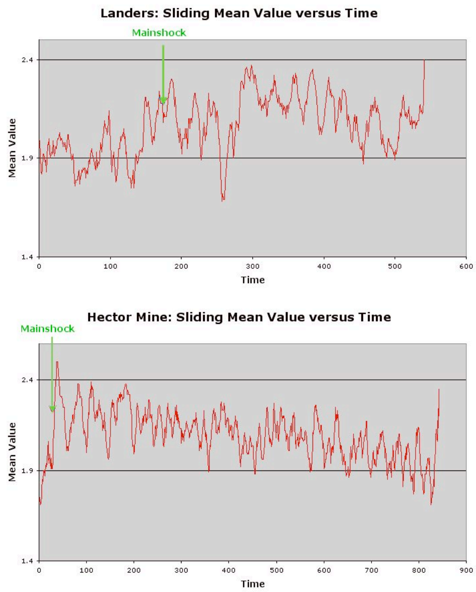


Figure 14: Plot Sliding Mean Value of the order 10 of magnitude versus Time for the a) Landers and b) Hector Mine earthquake. The green arrow marks the time of the mainshock

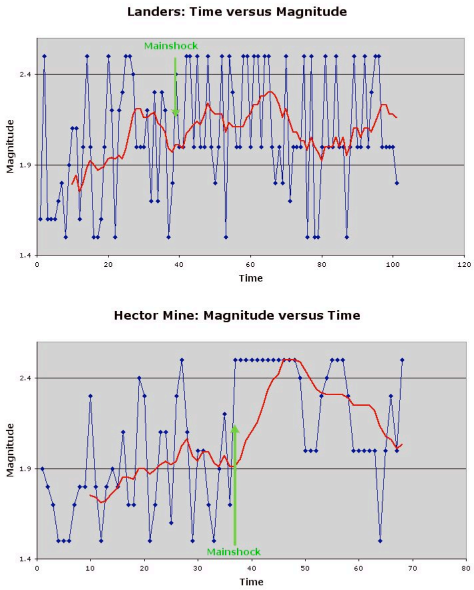


Figure 15: A close-up of the plot Sliding Mean Value versus Time in red and of the Magnitude versus Time in blue of the a) Landers and b) Hector Mine earthquake. The green arrow marks the time of the mainshock. Note that for the Landers sequence the plot does not begin at the first earthquake of the sequence.

6.2. Distance

The magnitude seems to match the effects heard in the sequences very well, but there are some earthquakes for mainshock and some aftershocks of the same magnitude, that does not sound similar. The reason for this effect can easily be found in the distance of earthquakes to the recording station. As earthquake are very small they are very sensitive to the distance. We compared earthquakes before and after the mainshock from approximately the same place and have got relatively similar sounding earthquakes, which supports the idea of the magnitude as a sound changing factor.

The effect of the distance also amplifies the bias of the magnitude as it can be seen in the sequences of stations further away. Small earthquakes will be less likely recorded in greater distance and thus the further away stations will have less smaller earthquakes. This effect acts on the aftershock sequences as well as on the sequences of earthquakes before the mainshocks, but a missing small earthquake does not bias the sequence of the overally smaller ”foreshocks“ as strong as in the case of the aftershock sequence.

7. Conclusions

7.1. Hypotheses

7.1.1. Thesis I

In Thesis I we proposed that earthquake before and after the mainshock can be distinguished. Although there is difference in the sound between the events before the mainshock and the aftershock directly after the mainshock, the difference mainly due to the magnitude change than to other factors. We also have not heard a significant difference between earthquakes of the same region and magnitude. This suggests that Thesis I could not be retained, as with an other selection concerning the magnitude the differences in the sound probably would disappear.

7.1.2. Thesis II

There are even fewer arguments that support Hypothese II, which suggests distinguishability of earthquakes before mainshock and foreshocks. As in Thesis I, the magnitude of the earthquakes plays a major role on the sound. This could explain the noticable foreshocks before Landers earthquake. The question is also if the really are significant at all, as there are only a two or three of them, they also might be a coincidence. Comparisons of events with the same magnitude showed no hearable difference so far.

7.2. The Audification

Our initial search did not reusal. We have not found any new information concerning the distinguishability of foreshock and aftershock with audification in this case. As we do not know if there is a difference in the waveform itself, the result is probably not surprising. Nevertheless, the method remains interesting and potentially useful. Some abilities of audification has been proved to be very useful in this study. Such as the ability to get a fast overview over a large and number of earthquakes. The sensitivity of the method concerning changes in distance, magnitude and other factors could add valuable information to some studies. However this method is no "Wonder-Weapon" for everything and has to be used as elaborated as other methods as well.

7.3. The Future Application of Audification

There are many potential application of the audification, now that a new processing toolbox has been created (see figure 16 for a screenshot):

- In the this study we did not discuss a potential effect of the b-values on the sound. A future topic of the audification could the potential sound change due to a spatial b-value variation. The earthquake catalog of the Parkfield region would be a suitable data source for such studies.
- As mentioned, artificial seismograms do not sound realistic. A possible application of the audification could be to improve the models that produced these seismograms.
- The method could also be used to construct and test new seismometers, as the ear is very strong at detecting differences.
- Also the audifiction of the background noise could be an useful application
- Listening to earthquakes is also an impressive experience and can thus be very useful for demostration and public outreach. The method could also be useful in teaching and education. A good example for this could be the fourier transformation.

The method itself could also be improved. There are still some factors and methods that have not been tried in this work and some factors that have not been tested accurately. Our next object is to elaborate a method to compensate the effect of the distance, the time and the magnitude. A possible way to

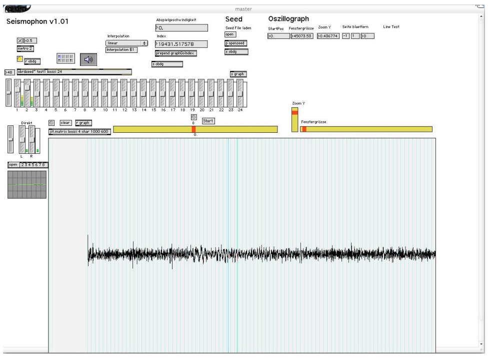


Figure 16: Screenshot of the newly developed audification toolbox

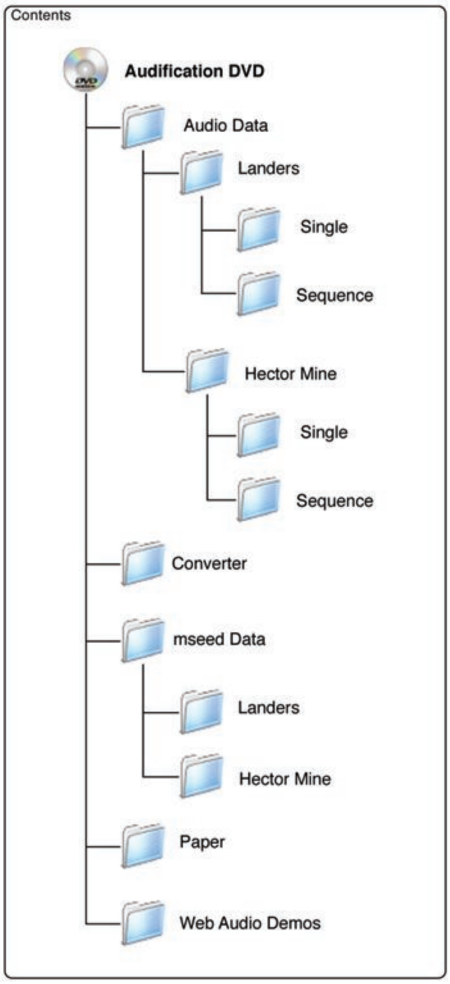
accomplish our goal is the application of different speedup factors for the compensation of temporal effect and the use of suitable gain correction function for the compensation of the distance and magnitude effect.

There are also efforts to use more complicated methods for the audifaction as the granular stretch and the fourier transformation.

A. Acknowledgments

I like to thank Stefan Wiemer and Florian Dombois for helping me writing this paper and Oliver Brodwolf for all the many nightly hours he has spent programming the earthquake to sound converter. I also like to thank my family for all their support and time.

B. DVD-Index


Contents
Audification DVD
Audio Data
Landers
Single
Sequence
Hector Mine
Single
Sequence
Converter
mseed Data
Landers
Hector Mine
Paper
Web Audio Demos

C. Converter Manual

C.1. Contents

The converter software consist of:

obrdseed: The seed to aif converter

mseed2aif: The mseed to aif converter

txt2aif: The sac-ascii and saf to aif converter

C.2. system requirements

The converters are currently only runable on Mac OS X.

C.3. Usage

All converter are command line based and have almost similar syntax.

C.3.1. obrdseed

This converter is first on we build. It is based on the software rdseed, an has due related syntax. A typical call of the program would be as following:

obrdseed -d -y ”44100 1.0 0.999 5 60” -q /aif/ -f /seed/MAJO-depth.seed

Where are the options as following:

-d This option means ”dump“ and is a relict of the original rdseed software. It was used to dump the waveform data of a seed file.

-y This option sets the parameter for the audifiaction (see later). The parameters has been encased by ” ”.

-q This option followed by a path specifies the output directory. If no path is specified the resulting file will be put into the same direction as the input file.

-f This option defines the path to the input file.

Note:

Due the heritage of the converter the original syntax of rdseed can be used. The seed converter can for example also convert mseed files, for this a dataless seed file with the corrensponding station has to be included with the option **-g**. For a full description of the rdseed syntax visit:

http://www.iris.washington.edu/manuals/rdseed.htm

C.3.2. mseed2aif

This converter syntax differs from the original syntax of the obrdseed converter. A typical call of the program would be:

mseed2aif -f /mseed/EHZ.mseed -d /aif/v1.aif -y ”44100 441 100 0.999 5 60”

Where are the options as following:

-f This option specifies the path to the input file.

-d This option followed by a path specifies the output path. If no path is specifed the output file will be in the same directory as the input file, and with the same name as the input file, but with the suffix .aif.

-y This option definies the parameter for the audification (see later).

C.3.3. txt2aif

The syntax of this converter is similar to the syntax of mseed2aif converter. A typical call would be:

txt2aif -f /ascii/060706-kurzenacht.SAF -d /aif/v2.aif -y ”44100 2205 10”

The option are similar to the option of the mseed2aif converter.

C.4. Audification Parameters

There are several parameters that have to be specified for the audifaction:

Sampling Rate: This parameter defines the output sampling rate of the resulting audio file and is written in Hz. A typical value would be 44100 Hz. The operation of the converter is simple, it converts sample by sample to the specified output sampling rate. A 20 Hz sampling rate seismogram into a 44100 Hz audio file would then results in a speed-up time of 2205.

Playback Speed: Normally the playback speed is the same as the output sampling rate. In the obrdseed converter this would be 1.0, in the txt2aif converter this would be sampling rate divided by 10, and in the mseed2aif converter this would be sampling rate divided by 100. Note that no interpolation will be done in the case of the playback speed of 1, the conversion will be a simple 1:1 conversion. The parameter can be set to other values than the sampling rate, this would result in speed-up if the value is bigger then the sampling rate, or slow down if the value is smaller. In the case of a slow-down the converter will do an interpolation in order to get the missing samples. Note that the pitch of the sound will change with different playback speeds.

We suggest to use a playback speed of 1 and do necessary speed-up or slow-down in the audio file player.

Damping: The damping factor is used to avoid distortion of the output file. We suggest to experiment with this parameter in order to find the right damping factor.

Lp Coefficient: This parameter is an option of the built in compressor. The lowpass filter is used in compressor to smooth the dynamic curve of the compressor. A higher value (near by 1) will result in a more shiftless reaction of the compressor. A typical value is 0.999.

Ref Level: This parameter is the reference level of the compressor. Signals below the reference level will be amplified while signals above the reference level will be damped. A typical value would be 5.

Percent: This parameter sets amount of compression in percent. A typical value would be 60.

The tree last parameters are for the built compressor and are option, note that if the compressor is used, all three parameters have to be defined. The compressor decreases the dynamic of the recording and can become very useful. We suggest to experiment with the compressor to find the right values.

The order of the parameter in the command line is as following:

"SamplingRate PlaybackSpeed Damping lpcoef reflevel percent"

C.5. Disclaimer

We are not responsible for anything this program does to your computer.

References

Bakun, W. H. and Lindh, A. G. (1985). The parkfield, california earthquake predicton experiment. *Science*, Vol. 229:p. 619–624.

Dodge, D. A., Berozy, G. C., and Ellsworth, W. L. (1995). Foreshock sequence of the 1992 landers, california earthquake and its implication for earthquake nucleation. *J. Geophys. Res.*, 100.

Dombois, F. (2001). Using audification in planetary seismology. In *Proceedings of the 2001 International Conference on Auditory Display, Espoo, Finland*, pages page 227 – 230.

Dombois, F. (2002a). Auditory seismology on free oscillations, focal mechanisms, explosions and synthetic seismograms. In *Proceedings of the 2002 International Conference on Auditory Display, Kyoto, Japan*.

Dombois, F. (2002b). Wann hören? vom forschen mit den ohren. In Schürmann, A. and Weiss, B., editors, *Chemie-Kultur-Geschichte, Festschrift für Hans-Werner Schütt anlässlich seines 65. Geburtstages*, pages 79–92. Verlag für Geschichte der Naturwissenschaften und der Technik.

Dombois, F. (2005). Zu hören wissen. In Koluches, B. and Weibel, P., editors, *unSICHTBARes. Algorithmen als Schnittstelle zwischen Kunst und Wissenschaft.*, pages 204–221. Beuteli Verlag.

Felzer, K. R., Abercrombie, R. E., and Ekström, G. (2003). Secondary aftershocks and their importance for aftershock forecasting. *Bulletin of the Seismological Society of America*, Vol. 93(No. 4):page 1433 – 1448.

Felzer, K. R., Abercrombie, R. E., and Ekström, G. (2004). A common origin for aftershocks, foreshocks, and multiplets. *Bulletin of the Seismological Society of America*, Vol. 94(No. 1):page 88 – 98.

Gerstenberger, M. C., Wiemer, S., Jones, L. M., and Reasenberg, P. A. (2003). Realtime forecasts of tomorrow's earthquake in california. *Science*.

Gutenberg, B. and Richter, C. (1944). Frequency of earthquakes in california. *Bulletin of the Seismological Society of America*, Vol. 34:pages 185–188.

Hurukawa, N. (1998). The 1995 off-etorofu earthquake: joint relocation of foreshocks, the mainshock, and aftershocks. *J. Geophys. Res.*, 108.

Imoto, M. (2005). Use of potential foreshocks to estimate the short-term probability of large earthquakes, tohoku, japan. *Pure and Applied Geophysics*, Vol. 162:page 1309 – 1318.

Lin, C.-H. (2005). Are foreshocks in taiwan considered as short-term earthquake precursor? Technical report, Institute of Earth Sciences, Academia Sinica.

Ohnaka, M. (1993). Critical size of the nucleation zone of earthquakes rupture inferred from immediate foreshock activity. *J. Phys. Earth*, Vol. 41.

Reasenberg, P. A. (1999). Foreshock occurrence before large earthquakes worldwide. *Pure and Applied Geophysics*, Vol. 155:page 355 – 379.

Roeloffs, E. (2000). The parkfield, california earthquake experiment: An update in 2000. *Current Science*, Vol. 79(No. 9):p. 1226–1236.

Schorlemmer, D., Wiemer, S., and Wyss, M. (2004). Earthquake statistics at parkfield:

1. stationarity of b values. *Journal of geophysical Research*, Vol. 109.

Utsu, T. (1961). A statistical study on the occurence of aftershock. *Geophys. Mag.*, Vol. 30:pages 521–605.

Wiemer, S., Gerstenberger, M., and Hauksson, E. (2002). Properties of the aftershock sequence of the 1999 m_w 7.1 hector mine earthquake: Implications for aftershock hazard. *Bulletin of the Seismological Society of America*, Vol. 92(No. 4):page 1227 – 1240.

Wiemer, S. and Wyss, M. (2002). Mapping spatial variability of the frequency-magnitude distribution of earthquakes. *Advances in Geophysics*, Vol. 45:page 259 – 302.

Woessner, J. and Wiemer, S. (2005). Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty. *Bulletin of the Seismological Society of America*, Vol. 95(No. 2):pages 684–698.

Ziv, A. (2006). On the role of multiple interactions in remote aftershock triggering: The landers and the hector mine case studies. *Bulletin of the Seismological Society of America*, Vol. 96(No. 1):page 80 – 89.