Soundscape Inner Earth

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The following text is the „static“ printout of the interactive document SoundScapeInnerEarth.cdf which can be viewed with the WolframResearch CDF-player.

https://www.wolfram.com/cdf-player/

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Foreword

Music and seismology have much in common, namely vibrations and waves. This has rarely been explored, let alone been exploited. As a small step into the first direction, the german composer Wolfgang Loos and myself produced the CD *Inner Earth, a seismosonic symphony* (Traumton records, 1999) which draws its sounds exclusively from seismic signals, in particular from those generated at volcanoes.

Although *Inner Earth* was not intended as a science project, it strengthened my belief that the analysis of seismic signals could potentially benefit from an acoustical approach (see also for example Simpson, 2005). I began to further explore the relationships between musical acoustics, the physics of vibrations (also through singing), and seismology. It turned out that through the concept of eigenvibrations and the role of overtones, fascinating similarities between these disciplines become rather obvious.

The advent of the CDF format (http://www.wolfram.com/cdf/) motivated me to generate the present interactive document. In addition to text, it includes a number of the sound and movie examples which can be read and listened to with the free CDF Player® (http://www.wolfram.com/cdf-player/).

1 Light, sound, and vibrations

1.1 Images of sound and the sound of images

The Earth moves constantly. And while it moves - on time scales from milliseconds to millions of years - it generates sounds. Any time. Everywhere. Silence does not exist. Most of the sounds of the Earth we can not hear, since their frequencies are below the audible range. As seismologists, which is what I have been doing for all my professional life, we sometimes claim to "listen" to the Earth. But actually, in the past we have been using visual perception more or less exclusively. An example for this approach is given in Fig. 1.1 which shows the seismogram, in other words a plot of the movement of the ground as a function of time, from a small earthquake from the Vogtland region in Germany. The three traces show the velocity of the motion of the ground in vertical (Z), north-south (N), and east-west (E) direction. The times t_P and t_S mark the arrival of the P-wave (compressional wave) and S-wave (shear wave), respectively.

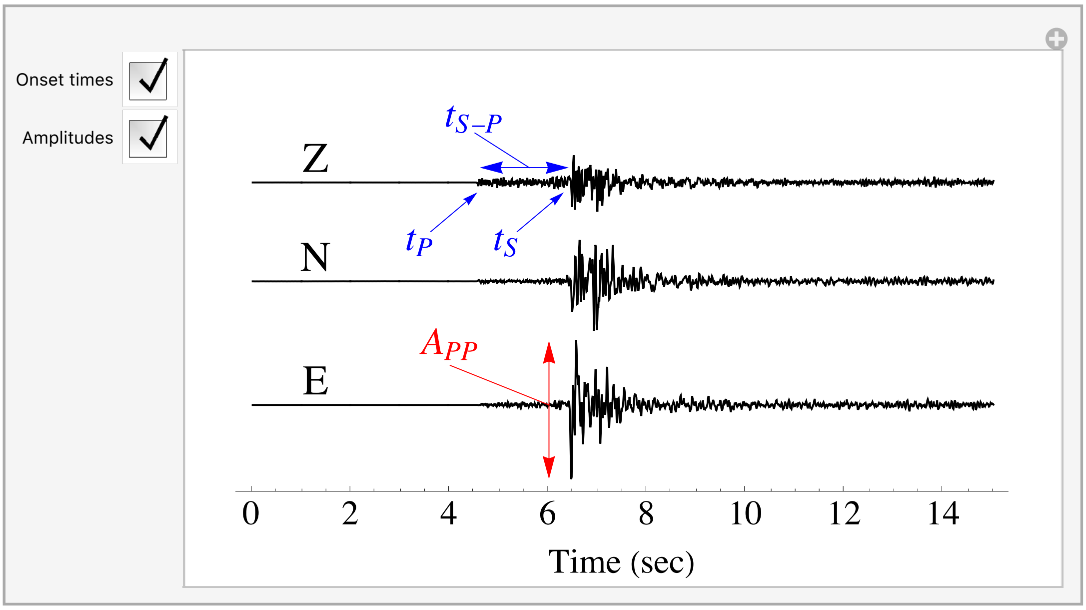

Figure 1.1. Seismogram of a small earthquake from the Vogtland region in Germany. The three traces show the movement of the ground (in terms of ground velocity) during the passage of the seismic waves in vertical (Z), north-south (N), and east-west (E) direction. The times t_P and t_S mark the arrival of the compressional wave (P-wave) and shear wave (S-wave), respectively.

A seismogram image contains a lot of information. The difference between the onset times t_P and t_S (labelled t_{S-P} in Fig. 1.1) is a direct measure of the distance to the earthquake. The peak-to-peak amplitude of the shear wave in the bottom trace marked by the red vertical double arrow (labelled A_{pp} in Fig. 1.1) is a measure of the magnitude (strength) of the earthquake. Just by looking at a seismogram, an experienced seismologist will know right away if he/she is looking at the record of an earthquake, a quarry blast, a truck or a broken instrument.

This example shows rather simple waveforms from a small microearthquake. If we look at seismic signals which have been recorded at volcanoes instead, typically the visual image becomes much more complicated (Figure 1.2). With one exception, the signals in the figure below are seismic signals which have been recorded at Mount Arenal in Costa Rica and Mount Merapi in Indonesia. To learn more about the nature of the exceptional signal, simply click on the image (make sure the sound of your computer is turned on) and you might recognize it.

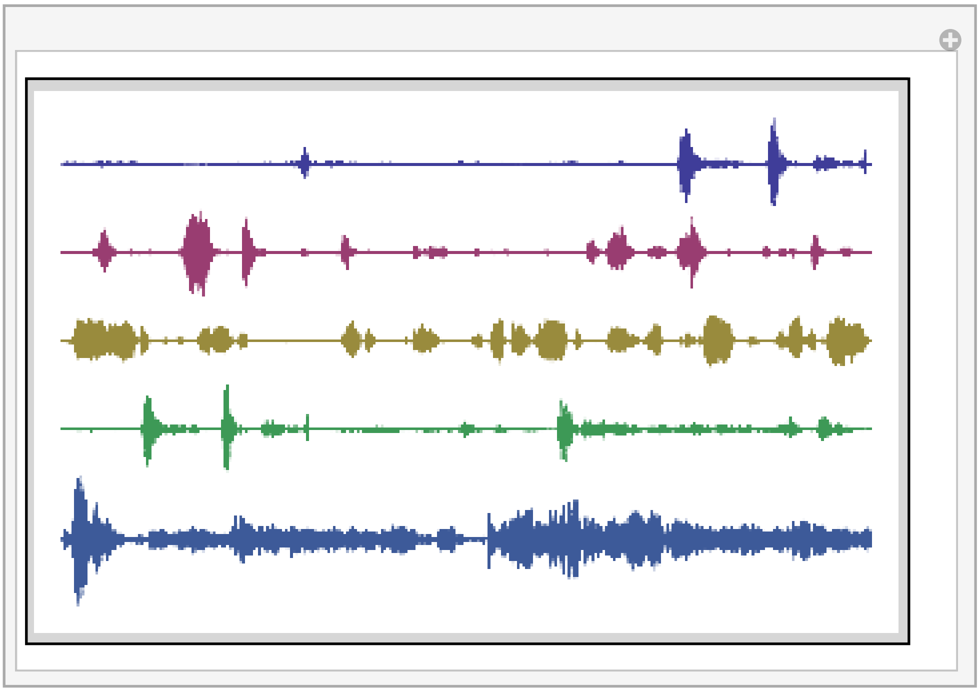

Figure 1.2. Example for the visual variability of seismic waveforms recorded at volcanoes. With one exception, the signals are seismic signals which have been recorded at Mount Arenal in Costa Rica and Mount Merapi in Indonesia. To learn more about the nature of the exceptional signal, click on the image.

What you have just heard if you have clicked on the image was the middle trace. This is obviously not a seismic signal but one of the the first recordings of a human voice, namely that of Thomas Alva Edison recorded in the year 1877, reciting the children´s poem *Mary had a little lamb*.

This example nicely demonstrates the fact that seismic and acoustic waveforms can look very similar if you stretch or compress the time axis properly. For a curious person, this similarity immediately raises the question: *How would it sound if we could hear all the seismic signals which are produced within the Earth?* For the german composer Wolfgang Loos and myself, this question marks the beginning of a artistic-scientific cooperation which resulted in the CD , *Inner Earth - A seismosonic symphony* which was published at Traumton records in the year 1999 (Loos and Scherbaum, 1999). Starting point for our journey into the soundscape of the Earth`s interior was simple curiousity on one hand, but on the other hand a feeling that an acoustical approach to seismic signals could be more than just playing games. Would we regard the sound of the Earth as musical sound or simply as noise? What could we say about the quality of sound? Would there be similarities to known instruments? How about melodies or rhythm? How about time scales?

All these are interesting questions which cannot be answered uniquely, but which can be fascinating for a seismologist as well as for a composer. Of course, the composer will be focus his/her interest on other aspects than the seismologist. For example on the question how seismic sound material can be used for compositions. We can imagine the challenge, if we think about the fact that we are used to musical time scales which are measured in seconds (with some exceptions such as Erik Satie´s Vexations or John Cage´s ASLSP which lasts for 639 years and which is currently performed in Halberstadt), while the typical time scales for processes within the Earth range from milliseconds to millions of years. Another challenge for a musician is to work with sounds which already exist. How can these be treated with compositional rules established for conventional sounds?

As seismologist I was primarily interested in the question how far one could push the model that the Earth and parts of it are objects that can vibrate and as such are musical instruments? Is it possible to anticipate the kind of sound to expect? Would a sound corresponding to an interesting looking seismogram, e. g. such as the one shown in Figure 1.3 correspond to an interesting acoustical impression? This of course is a question which interests the composer equally well. And finally, I was interested in the question if we could benefit scientifically by approaching seismic data using our ears?

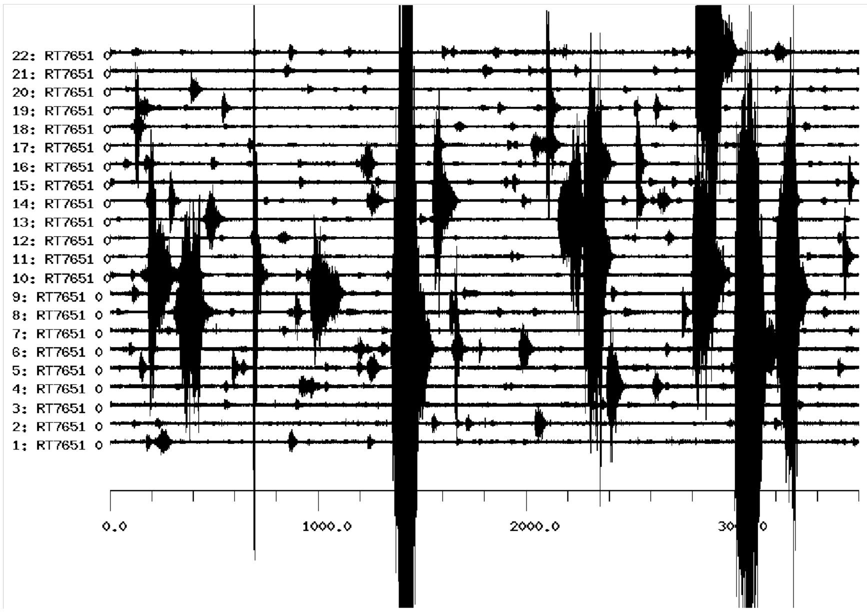

Figure 1.3. Seismic signals from Mount Merapi in Indonesia during a rather active period. Each horizontal trace corresponds to a single hour of recording.

The reason why we can`t hear seismic waves directly is the fact that the audible range for humans lies between 20 Hz and 20 KHz. Most of the seismic signal frequencies fall far below that. Therefore, in order to make seismic signals audible, the pitch of the signals has to be transformed into a range which we can directly hear. In musical terms, this is referred to as pitch shifting. This is not without problems, as is illustrated with the example given in Fig. 1.4.

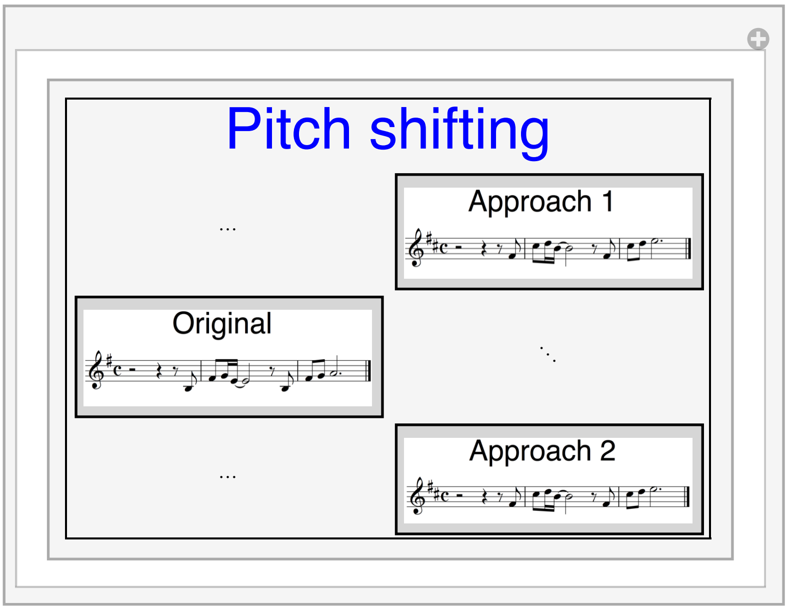

Figure 1.4. Examples for different approaches to changing the pitch of a sound. Press the different buttons labelled *Original*, *Approach 1*, and *Approach 2*, to hear the sound examples explained in the text.

Fig. 1.4 illustrates two different approaches to changing the pitch of a sound. If you click on the button labeled *Original*, you will hear the geman singer Michael Schiefel (Traumton Records) sing the short phrase *The summer smiles, the summer knows*. To transpose it to higher pitch by a fifth (which corresponds to a frequency increase of 50%) we could ask the singer to sing it in a different pitch (trying to stay in the same voice register). Click on button *Approach 1* to hear the result. If we have recorded the melody on a tape recorder, we could also get a higher pitch by sspeeding up the tape on playback and we would obtain a different type of transposition (Click on button *Approach 2* to hear the result). The distortion of the sound perception accompanying the second method is sometimes called *Mickey Mouse effect*.

Of course, the Earth will not do us the favor to play her sound in a pitch range suitable to our ears, but I have to admit that both transpositions in Figure 1.4 have been produced by software. This demonstrates that the audible result of a transposition will criticially depend on the method which is used. Therefore, I want to approach the question regarding the sound of the Earth in a completely different way, namely by making use of sound generation in well known musical instruments. There we have a clear understanding of the sound generation. If we manage to obtain a physical model of the properties of what could be called a harmonic sound, we could subsequently ask the question where in Earth we could expect to find similar mechanisms, even if they happen at lower frequencies. For this purpose we will have to dive into the field of musical acoustics.

1.2 Optical and acoustical prisms

The key towards understanding the properties of sound lies in what is called the sound spectrum. One can envision a sound spectrum as a musical equivalent to the color spectrum of visible light (Fig. 1.5). Sending white light through a prism will cause a separation into its color-, or spectral components (Fig. 1.5). Each color corresponds to a different frequency. If we would plot the intensity of each color as a function of frequency, we would obtain the color spectrum of light (Fig. 1.5).

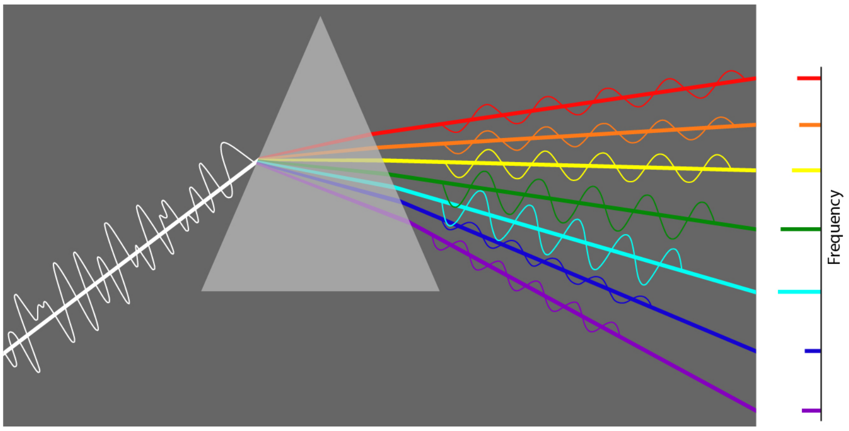

Figure 1.5. Sending white light through a prism will cause a separation into its color-, or spectral components (redrawn after Bracewell, R. N., The Fourier Transform, Scientific American June 1989, p. 86-95).

In a similar way - by some sort of acoustical prism - we can split up an arbitrary sound into its spectral components. Individual colors correspond to what is called pure tones, as they are produced by a tuning fork in stationary oscillation. In other words, a sound spectrum can be seen as a recipe to construct a sound by superposition of pure tones. In optics, frequency determines the color while in acoustics it determines the pitch of the pure tone. An example is given in Fig. 1.6. If you press the button you will be listening to the note C´ played on a guitar. The plot itsself shows the corresponding sound spectrum.

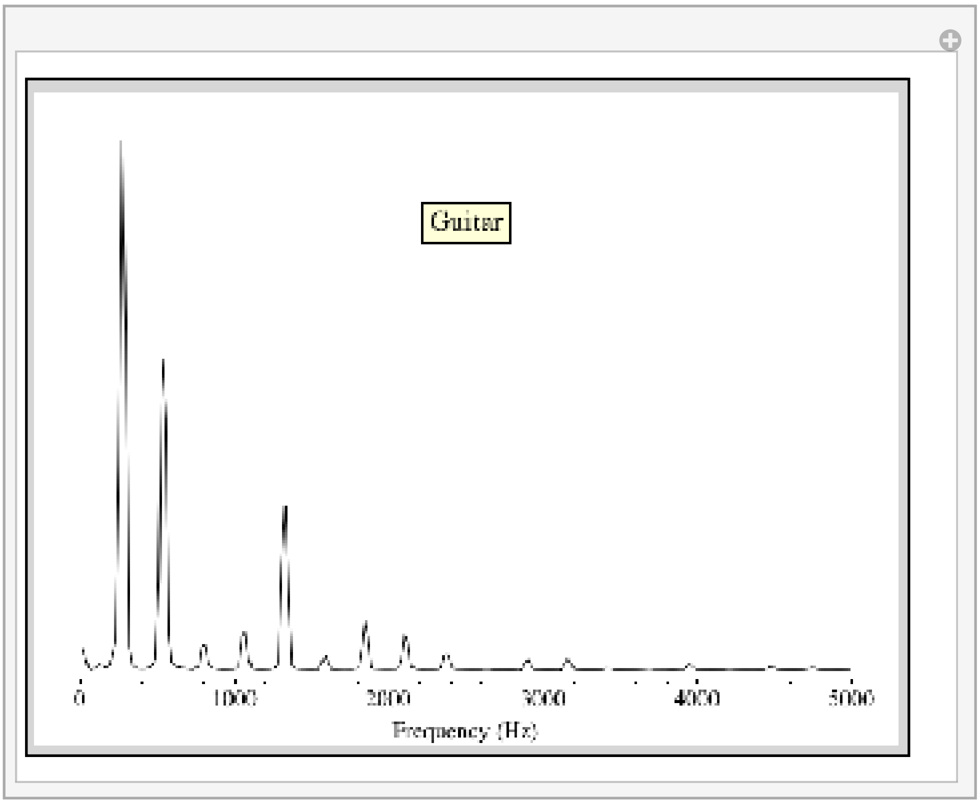

Figure 1.6. Sound spectrum of the note C´played on a guitar. Press button to hear the sound.

Each vertical peak corresponds to a single pure tone. One can see right away, that the sound is made up by several pure tones which are called partials. Interesting to note is the fact that the partials show a very regular frequency spacing. If one would measure the frequencies for each partial, one would realize that they are all multiples of a particular frequency which is called the fundamental. The others are called overtones.

In Fig. 1.7 you see (and can hear) the sound spectra of different instruments, all playing the same note C4 (262 Hz). Click on the individual buttons to hear a particular instrument play the same note (C4 which corresponds to a frequency of 262 Hz). The timbre, also called sound color, which is the property in which sounds differ that are played with the same pitch and the same loudness, is controlled primarily by the relative strength of the partial tones. You can see from the structure of the spectra that the guitar as well as the flute and the voice produce sounds in which the spectral components show a very regular frequency spacing. Sound with this type of spectra is called **harmonic**. We can see that a drum signal or the noise signal don`t have this property.

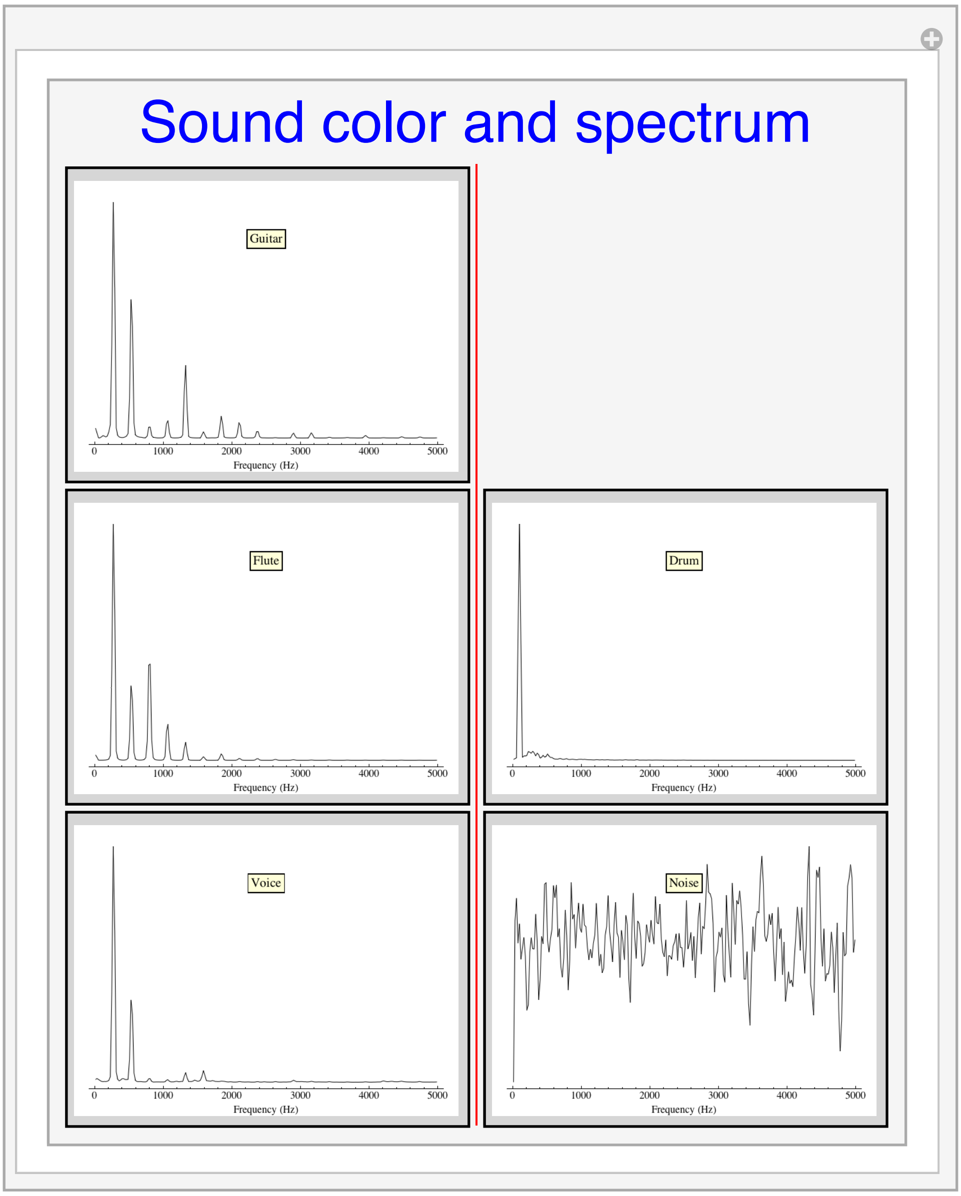

Figure 1.7. Sound spectra of different instruments, all playing the same note C' (256 Hz). Click on the individual buttons to hear the corresponding sounds.

1.3 Sound generated by musical instruments

Naturally, the question arises what causes the regular spectral structure of harmonic sound. The reason lies in what physicists call *boundary conditions*, in our case the boundary conditions of vibrating bodies. Expressed in common language, the reason is simply that a body of finite size can only vibrate in certain vibrational patterns. This will become fairly obvious when we look for example at how a string, which is fixed at both ends, can vibrate.

1.3.1 Strings

When we pick a guitar string or a string of any string instrument, it can only oscillate such that the ends remain at rest. As a consequence, only particular oscillatory patterns can develop. These allowed oscillations are called **eigenvibrations** of the string or **modes** or **partials**. The corresponding frequencies are called **eigenfrequencies**. This is illustrated in Fig. 1.8 for the first ten of the allowed modes of a fixed string. The first mode is called the fundamental, the higher modes are called overtones. The second mode would correspond to the first overtone, the third mode to the second overtone, and so on.

Figure 1.8. Select a mode number with the slider and click on the play button (▸) to start the oscillation of the selected mode. L is the length of the string, λ is the wavelength of the selected mode. Modified from “Transverse Standing Waves” from the Wolfram Demonstrations Project (http://demonstrations.wolfram.com/TransverseStandingWaves/) by Ken Caviness. See also

You can see in Fig. 1.8 that the wavelengths of the modes become shorter and shorter with increasing mode number. For the first mode (the fundamental) one can see in Fig. 1.8 that only half of a full sinusoidal oscillation fits onto the length of the string L. Therefore, the wavelength λ of the first mode is two times the length of the string ($2\,L$). The wavelength of the second mode is half as long ($\frac{2\,L}{2}$), that of the third mode one third ($\frac{2\,L}{3}$), and so on. In other words, the wavelengths of the mode are integer fractions of the wavelength of the fundamental mode. Since wavelength and frequency are inversely proportional to each other, a fixed string can produce only frequencies which are an integer multiples of a fundamental frequency. This causes the regular structure of the sound spectrum of a string.

The key to understanding that a fixed string (and therefore any string instrument) will always have a harmonic sound spectrum is the fact that **any arbitrary oscillation of a string is a superposition of eigenvibrations**. The relative strength of the individual modes controls the character (timbre) of a sound.

Hence any sound generated by a string is always a superposition of (in principle infinitely many) partial tones, the frequencies of which are all integer multiples of the frequency of the fundamental mode. The amount by which a particular partial tone contributes can be controlled to some degree by the way the string is excited (cf. http://demonstrations.wolfram.com/TheVibratingString/). By picking a guitar string in the center, the fundamental mode will contribute to the sound to a larger degree than if it is picked close to one of the ends. One can even fully suppress the fundemental mode, by lightly touching the string at the center (which is where the fundamental mode would have its largest oscillation) with one of the left hand fingers and strongly picking the string with one of the right hand fingers at a different position. These are the so-called flageolets an example of which is given in Fig. 1.9.

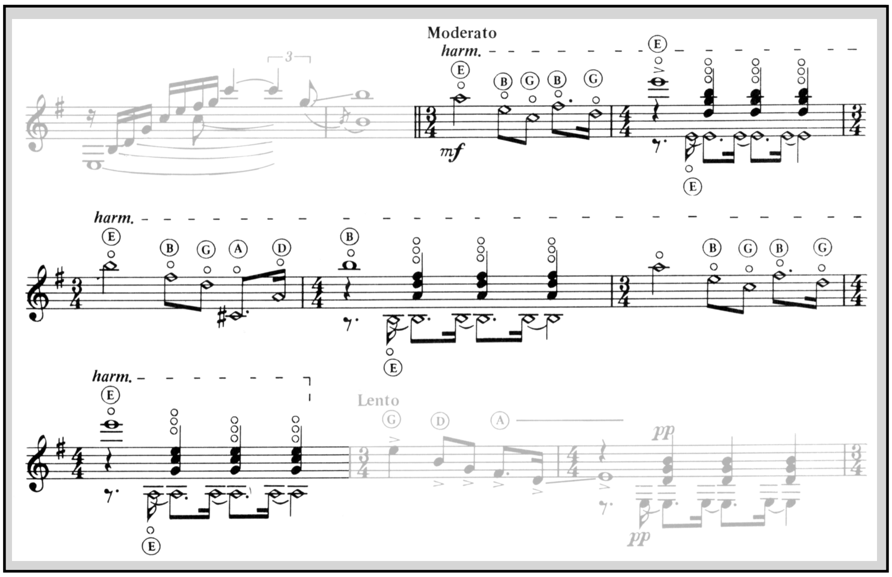

Figure 1.9. The six bars above from the prelude No. 4 in e-minor by H. Villa-Lobos (Rio, 1940) only use overtones, the so-called flageolets. These are produced by lightly touching the string at certain positons with one of the left hand fingers and strongly picking it with one of the right hand fingers. This way the fundamental is suppressed and the overtones dominate the sound.

At this point I want to wrap up for a moment.

- The regular (harmonic) spectrum of a string is caused by the fact, that since the string is fixed at both ends, only particular oscillatory patterns can develop and the frequencies of all partial tones have to be integer multiples of the fundamental frequency.
- The relative strengths of each partial essentially controls the sound character (timbre).
- The excitation of overtones, on the other hand, is strongly controlled by the way the string is played. An example is given in Fig. 1.9.

1.3.2 Flutes

For similar reason as for the fixed string (geometrical constraints on the oscillatory patterns that can develop) we can expect regular sound spectra in other instruments as well, e.g. a flute. Here the quantitiy that oscillates is the set of air molecules, as simulated below for the first three partials (Fig. 1.10) Since the air can move freely at the open ends of the pipe, the displacements will always be maximum at these positions. For each of the modes, the row below each particle distribution image displays the distribution of maximum particle displacement within the pipe. The bottom row shows the corresponding distribution of maximum air pressure.

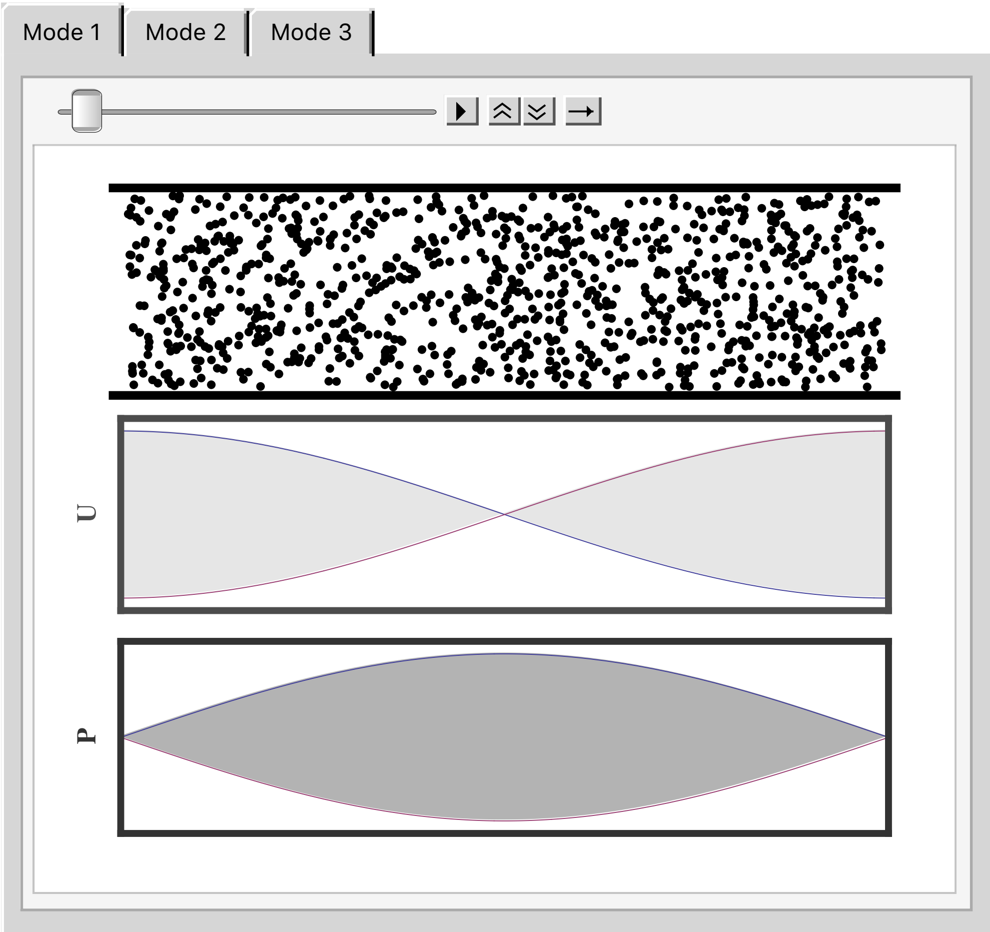

Figure 1.10. The open flute. The three different tabs show the eigenvibrations for the first three eigenmodes (fundamental and the first two overtones) are shown. The top row in each plot shows the movement of the air molecules. Since the air can move freely at the open ends of the pipe, the displacements (middle rows) will always be maximum at these positions. The bottom rows show the corresponding distribution of air pressure. Click on the play button (▸) to start the oscillation of the selected mode. Modified from code obtained from Daniel Russell.

Again, with increasing order of the overtones, the wavelengths be come shorter by an integer ratio: 1 : 1/2 : 1/3. Hence, the corresponding eigenfrequencies increase in the inverse ratio: 1: 2 :3. This is slightly different for a stopped pipe, which is closed on one end (Fig. 1.11).

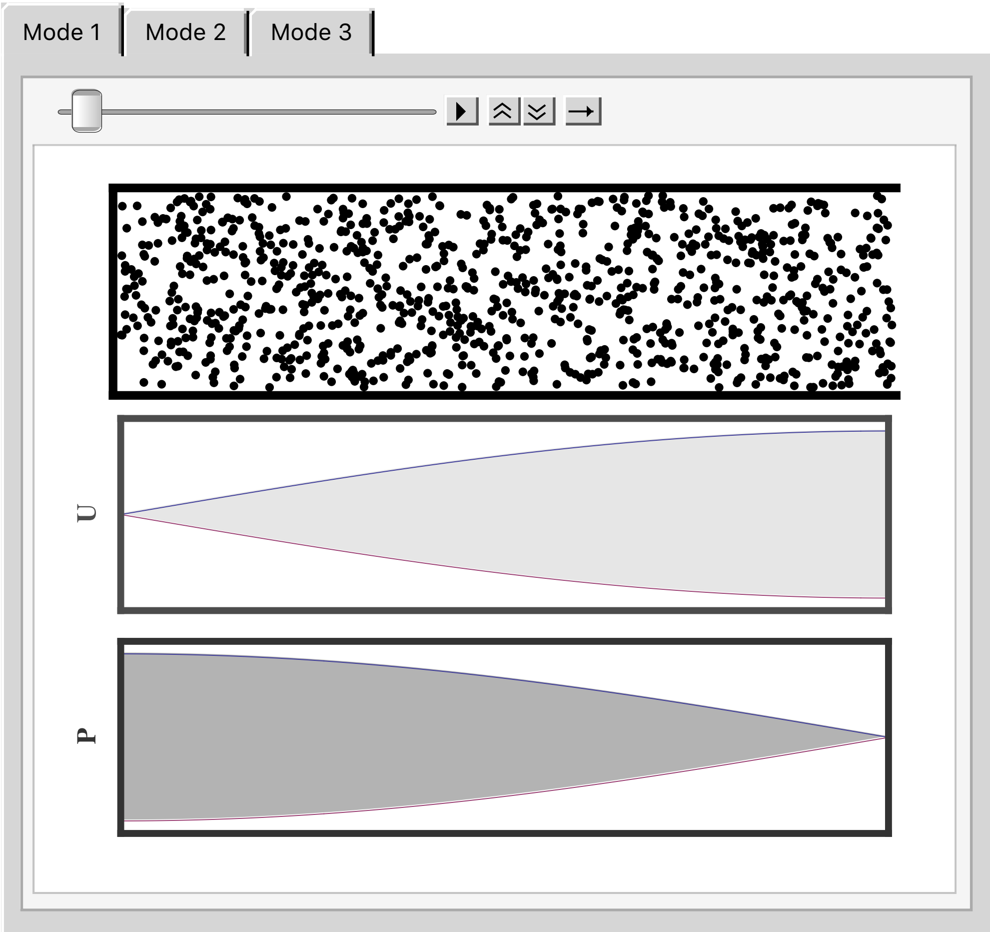

Figure 1.11. The stopped pipe. The three different tabs show the eigenvibrations for the first three eigenmodes (fundamental and the first two overtones) are shown. The top row in each plot shows the movement of the air molecules. Since the air can move freely only at the open end of the pipe, the displacement (middle rows) will always be maximum at this positions but will be zero at the closed end, where the particles are forced to rest. This causes maximum air pressure (shown in the bottom panel) to develop. At the open end, the particles can move freeely and the pressure is zero. Click on the play button (▸) to start the oscillation of the selected mode. Modified from code obtained from Daniel Russell.

The asymmetry in the displacement and pressure of the air molecules generates eigenmodes for which the wavelength ratio is 1: 1/3: 1/5 and for which the frequency increase at a ratio 1:3:5. **What will become important for the following is the fact that the ratio is still an integer ratio.**

1.3.3 Drums

For a drum it is usually a circular membrane which is excited to oscillate as shown in Fig. 1.12. Here the eigenvibrations of the membrane and their corresponding frequencies determine the sound spectrum.

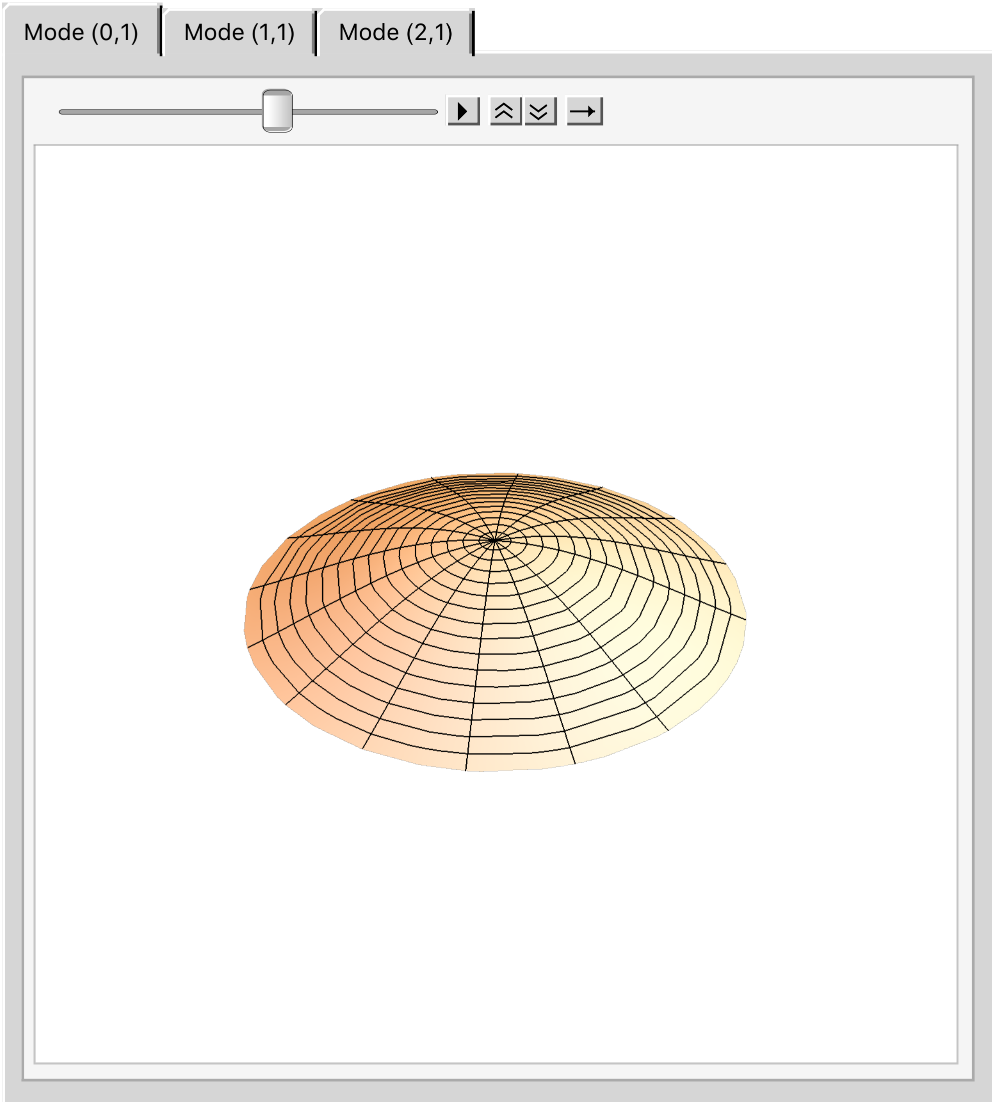

Figure 1.12. Eigenvibrations of a circular membrane. The numbers in parenthesis are used to categorize the type of oscillation. The first number indicates the number of diameters on which there is no displacement, the second index marks the number of concentical circles which stay at rest.

For membranes it is interesting to note that the ratios of the overtone frequencies to the fundamental frequency f_0, which is that of the (0,1) mode, are no longer integer values as for the string or the flute. The frequency of the (1,1) mode is $1.593 f_0$ and 2.135 f_0 for the (2,1) mode. This on the other hand is closely related to a sound quality which we regard as percussive. The (mathematical) reason for this breakdown of the integer-ratio relationship between the mode frequencies is related to the fact that the vibration of circular membranes can no longer be described by simple superposition of sine and cosine functions but requires a different mathematical description (cf. http://demonstrations.wolfram.com/NormalModesOfACircularDrumHead/).

At this point we can summarize:

- The character of sound is determined to a major degree by its spectral structure. A pure sine wave like that of a tuning fork does not sound very exciting.
- Harmonic sound is related to a spectrum in which the overtone frequencies are integer multiples of the fundamental frequency e.g., for a string and a flute.
- Percussive sound is related to non-integer ratios of eigenfrequencies, e.g., for a drum.

I have to admit that this is a very simplified model, in which a number of important effects which strongly contribute to the character of sound as well are ignored. We are basically restricting ourselves completely to the stationary state and ignoring all transient effects. For the following, however, this model will be completely sufficient.

2 Soundscape Earth

Now we can start our journey into the interior of the Earth and try to find out what kind of vibrations and sounds are generated there.

- Can we expect overtone rich signals to be generated within the Earth at all?
- If yes, what is the structure of the corresponding spectra?

In the following, I will give examples from very different areas of seismology. However, always from the perspective of musical acoustics. First, I will discuss acoustical measurements from the Vogtland earthquake region in Bohemia. Subsequently, I will analyze the acoustical role of shallow sediments, as they are common for many topographic basins. I will try to convince you that volcanoes, flutes, sirens and the human voice have much in common and finally speculate about how the Earth as a whole might hum.

2.1 Earthquakes from the Vogtland region

Let`s start out with some *country music* from the Vogtland area in Bohemia, the border region between Germany and the Czech republic. During the last century, the Vogtland region has been an area of several large earthquake swarms with thousands of weak earthquakes within a couple of weeks. Of interest in the present context is the fact that people from the area have repeatedly reported that they have heard the earthquakes. In order to better understand the generation of such signals, a combination of seismometers and microfones was set up at the seismic station WER shown in Fig. 2.1.

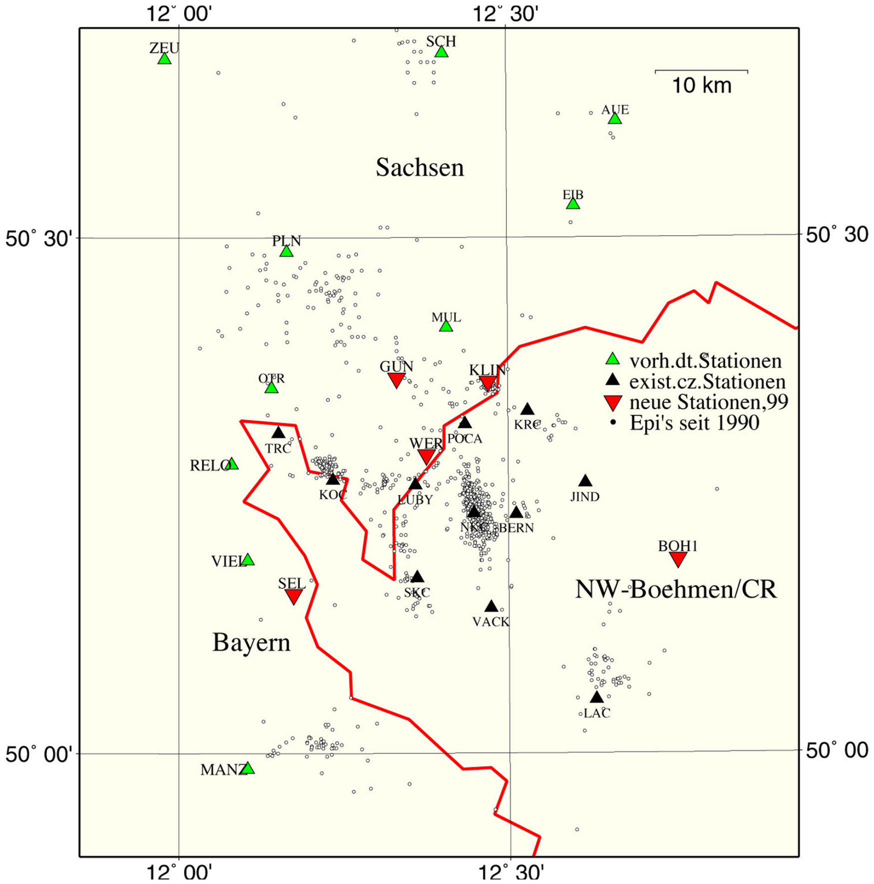

Figure 2.1. Earthquake epicenters (black dots) in the Vogtland region between 1990-1999. The solid triangles mark seismic stations which were temporarily in operation during that time. Station WER is located close to the center of the map. Source: Central Seismological Observatory of the Federal Institute for Geosciences and Natural Resources (http://www.bgr.bund.de/EN/Home/homepage_node_en.html).

The result of one of these combined seismic and acoustic records is shown in Fig. 2.2. H owever, the microphone signals wich have been recorded so far are still a little bit too weak to be really audible well, even if we increase there frequency by roughly 3 octaves using the pricinple of accelerated playback (from 100 to 1000 Hz sampling frequency). The record is still dominated by the background noise. If you click on the images you will hear the earthquake signal as a short but very weak beat.

Figure 2.2. Simultaneous records of seismic and acoustic signals from a microearthquake in the Vogtland region (Krüger and Vollmer, pers. comm.). Shown on the left is the seismogram, shown on the right the microfone recording which was obtained at the same time. Click at the images s to hear the records.

We also obtain the impression of a percussive signal when we look at the corresponding spectrum (Fig. 2.3) and compare it with our expectation of an harmonic spectrum (Fig. 1.7). One can see in Fig. 2.3 that the spectrum does not show the regular structure which we would expect froma harmonic sound. Instead, the intensities show a single dominating maximum slightly below 20 Hz. For most of us this is still slightly below the audible range.

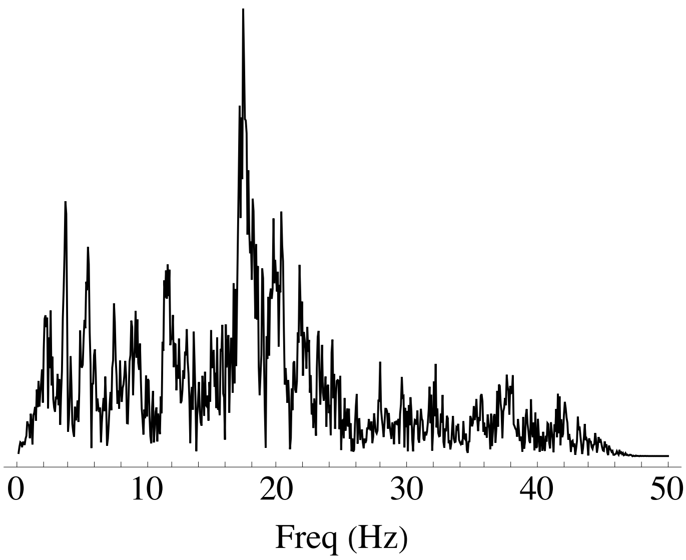

Figure 2.3. Spectrum of the seismometer record shown in Fig. 2.2.

Earthquake signal usually don`t have a regular spectral structure which is rich in overtones. Therefore, they appear percussive. There are exceptions, however, as will be discussed below.

2.2 The acoustical effect of soft sediments

Harmonic spectra can develop for example in cases when seismic waves run into soft sediments overlying a more rigid structure. In Fig. 2.4 some of the related features are demonstrated. Each tab shows a vertical cross-sections through the Earth. The upper bound of each panel corresponds to the surface of the Earth. In the case of a homogeneous halfspace (first tab), a wave which hits the surface from below will be reflected back into the lower subsurface. The complete wavefield is the superposition of the direct and the reflected wave. In case there is an soft sediment layer directly below the surface (second tab), the layer interface will act as an additional reflector and part of the energy will bounce up and down between the interface and the surface and might even generate some sort of standing waves. In reality, the seismic waves in such layers will be strongly attenuated, that means part of their energy will be transformed into heat. This is simulated in the third movie (third tab), which probably comes closest to reality.

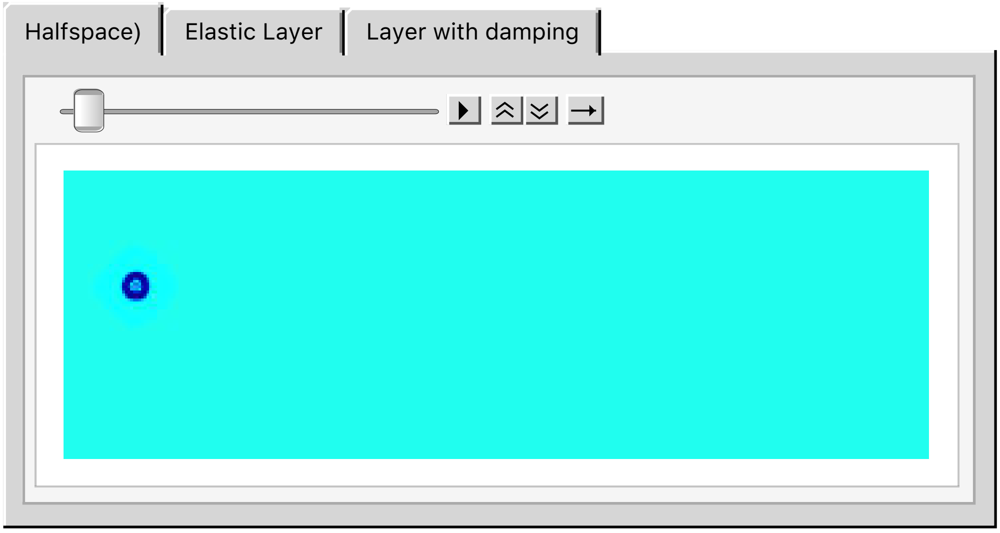

Figure 2.4. The acoustical effects of soft sediments. Click on the play button (▸) to start the wave propagating. Each tab corresponds to a different model situation. The upper bound corresponds to the surface of the Earth. Simulations courtesy of Sebastian Martin.

Figure 2.5 shows snapshots of the wave propagation, seismograms, and spectra for the three model situations from Fig. 2.4. In the first case, the spectrum is more or less flat. In the second case, we clearly recognize a regular overtone structure. In the third case, only a single peak remains, the others have been filtered out by damping.

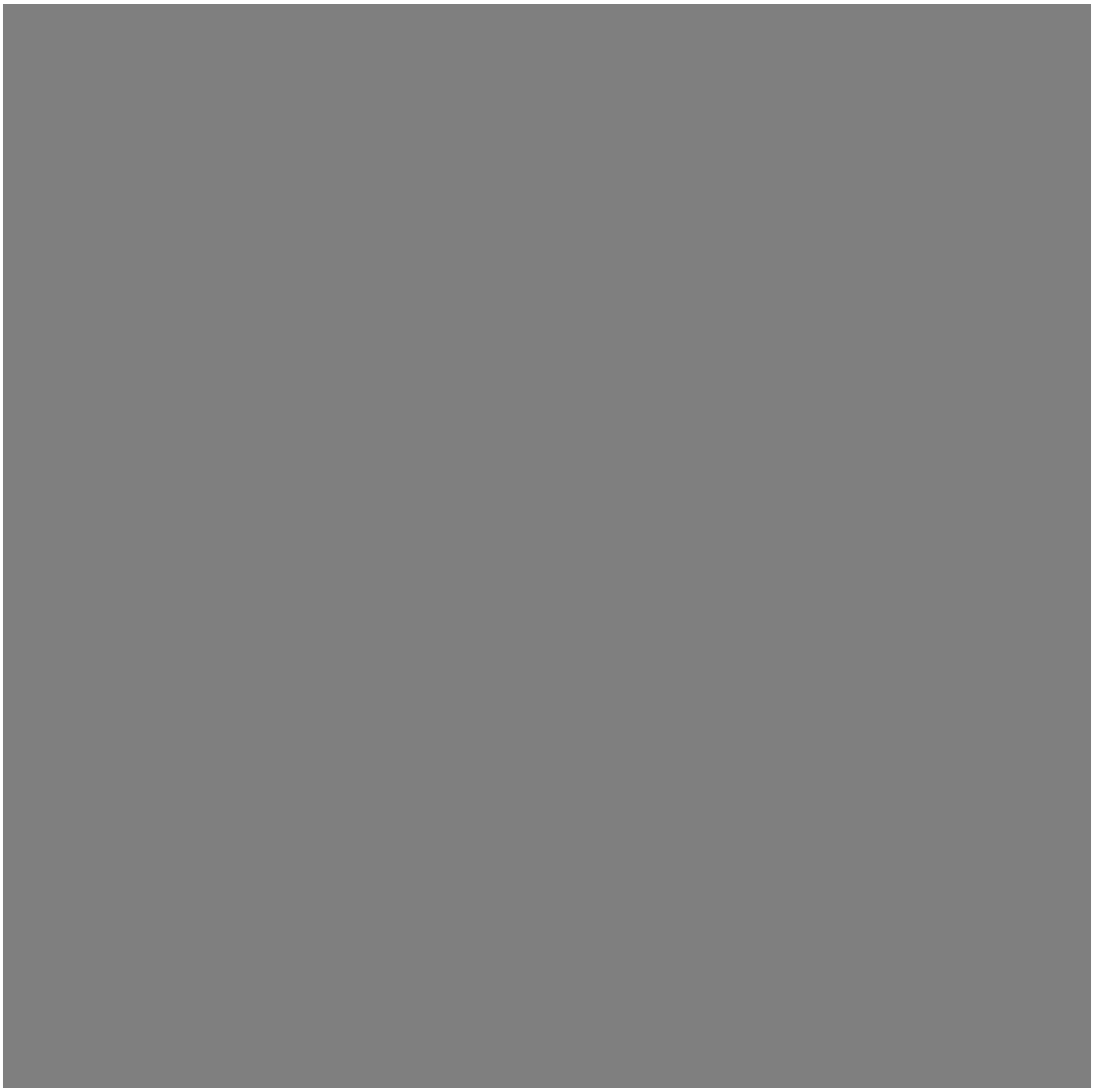

Figure 2.5. Snapshots of wave propagation, seismograms, and spectra for the three model situations shown in Fig. 2.4. If you click on the centeral images, you can hear the corresponding signal, transposed into the audible range using the principle of accelerated playback. You can clearly hear the differences between case a (single beat), case b) (echos which correspond to the multiple reflection within the layer), and case c) in which these echoes are barely audible since they are supressed by daming (basically exchanging seismic wave energy into heat).

Although only a single spectral peak remains in the third case, that does not mean it is of little importance. Actually, in areas with soft sediment coverage, a lot of effort is spend to determine this peak, because at this frequency the shakebility of the subsurface is greatly increased (Fig. 2.6). In many situations these frequencies are closely related to the resonance frequencies of the sediments. The cross section through the Lower Rhine Embayment in Fig. 2.6 demonstrates how these frequencies - determined by the so-called H/V method - change as a function of the geological structure. The lower panels show selected spectra. The peak frequencies range from values of 5 Hz in the east up to values below 0.2 Hz in the west where the thickness of the sedimentary cover reaches values of several hundreds of meters.

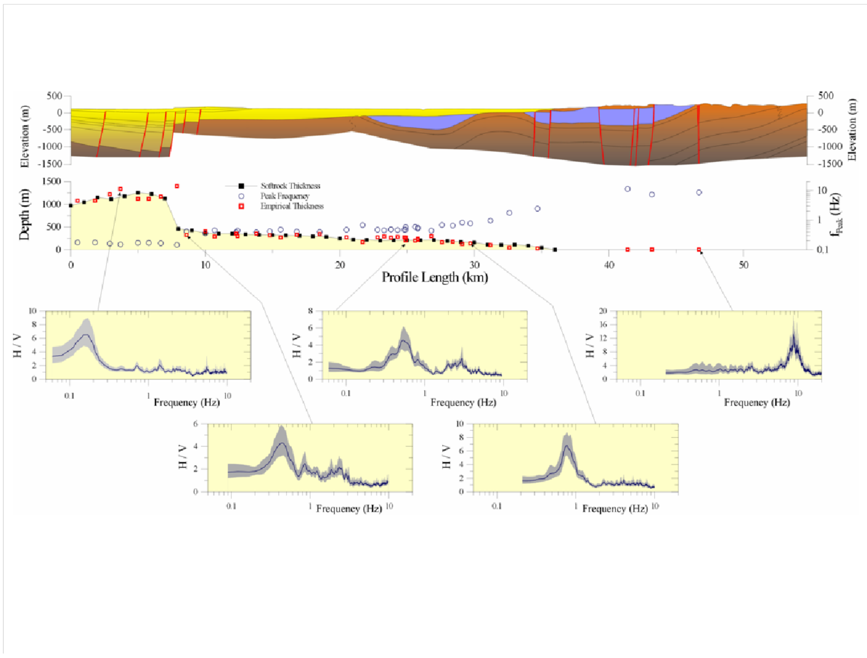

Figure 2.6. Cross section of H/V peak frequencies from ambient vibration measurements through the Lower Rhine Embayment/ Germany (Hinzen et al., 2004). In high impedance situations these frequencies are closely related to the resonance frequencies of the sediments.

2.3 Volcanoes

In most cases, the spectral structure of earthquake signals is rather boring. Only in exceptions they show acoustically interesting features. Ususally, earthquake signals sound like some sort of percussion instrument. Acoustically, it gets much more interesting and variable if we turn to signals generated at volcanoes. Below you see examples for this variability (Fig. 2.7). Volcano seismologists use a particular coding scheme which puts them into different signal classes according to their waveform. Some of these types are shown in Fig. 2.7.

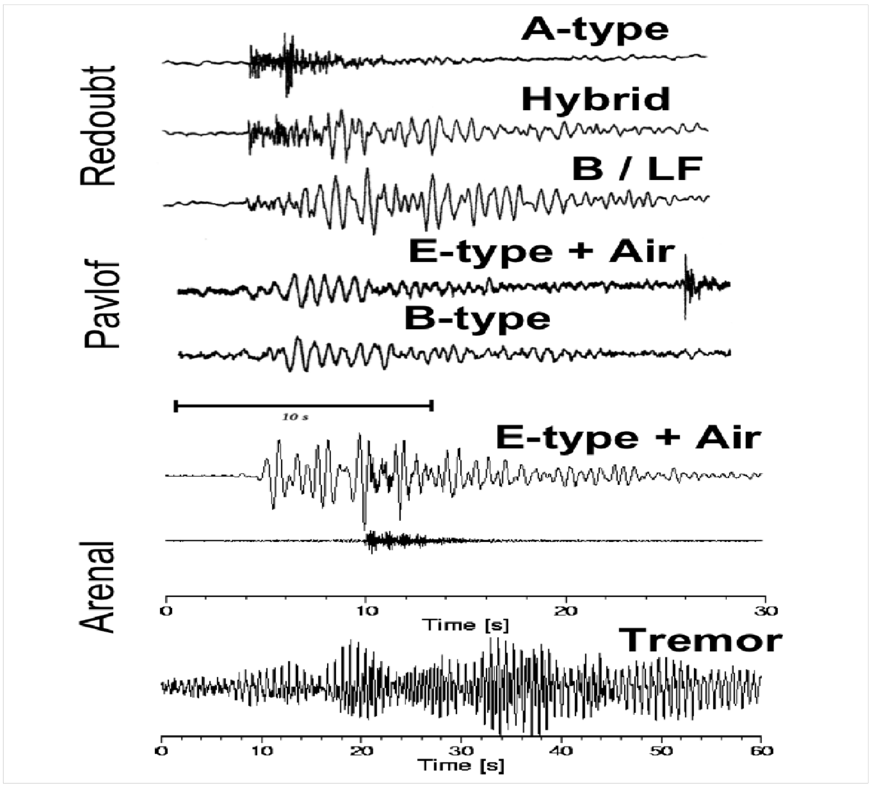

Figure 2.7. Examples for the variety of seismic waveforms recorded at volcanoes (after Ohrnberger, 2001).

One of the prime study regions for these effects is the island of Java with its 35 active volcanos (Fig. 2.8). Acoustically two of them are particularly interesting. These are the Mt. Semeru in eastern Java and the Mt. Merapi in central java.

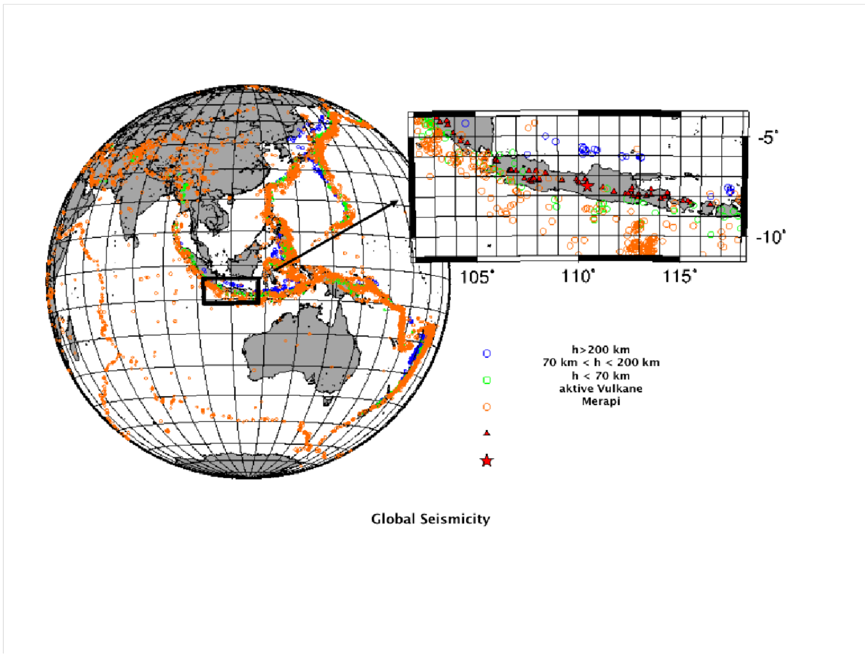

Figure 2.8. The island of Java, home of 35 major active volcanoes.

Below you see the recording of a what is called a volcanic tremor signal from Mt. Semeru (Fig. 2.9). The top trace shows the ground motion while the spectrum is displayed in the bottom panel. The spectrum - very much in contrast to earthquake signals - shows a regular frequency spacing, similar to that of a flute (cf. Fig. 1.7). The total length of the signal is roughly 6 minutes. These signals are believed to be generated by instabilities within the gas/magma system.

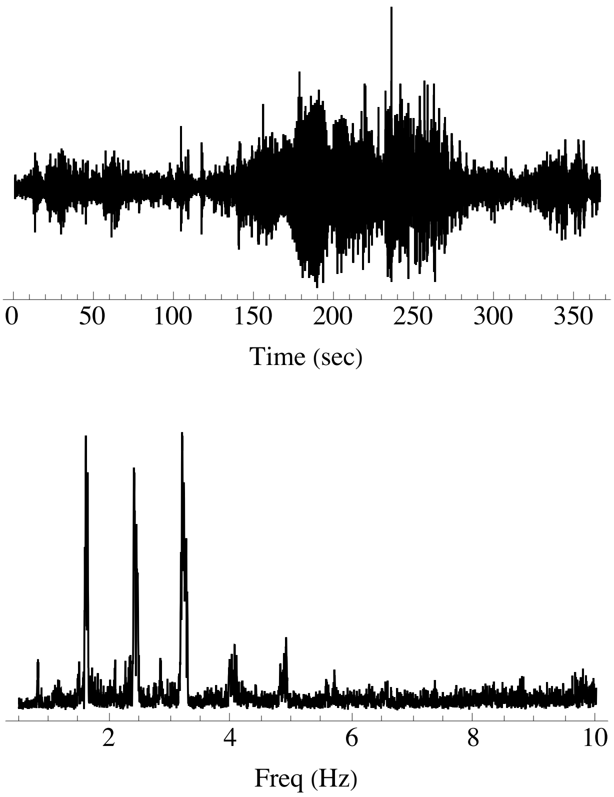

Figure 2.9. Volcanic tremor signal (top trace) and corresponding spectrum (bottom trace) from Mt. Semeru (Schlindwein et al. 1995). The spectrum shows regular frequency spacing, similar to that of a flute (cf. Fig. 1.7).

Below, you see the same signal in a slightly different display (Fig. 2.10). This kind of plot, which is called a time-frequency plot or spectrogram, shows very nicely how the overtones develop as a function of time.

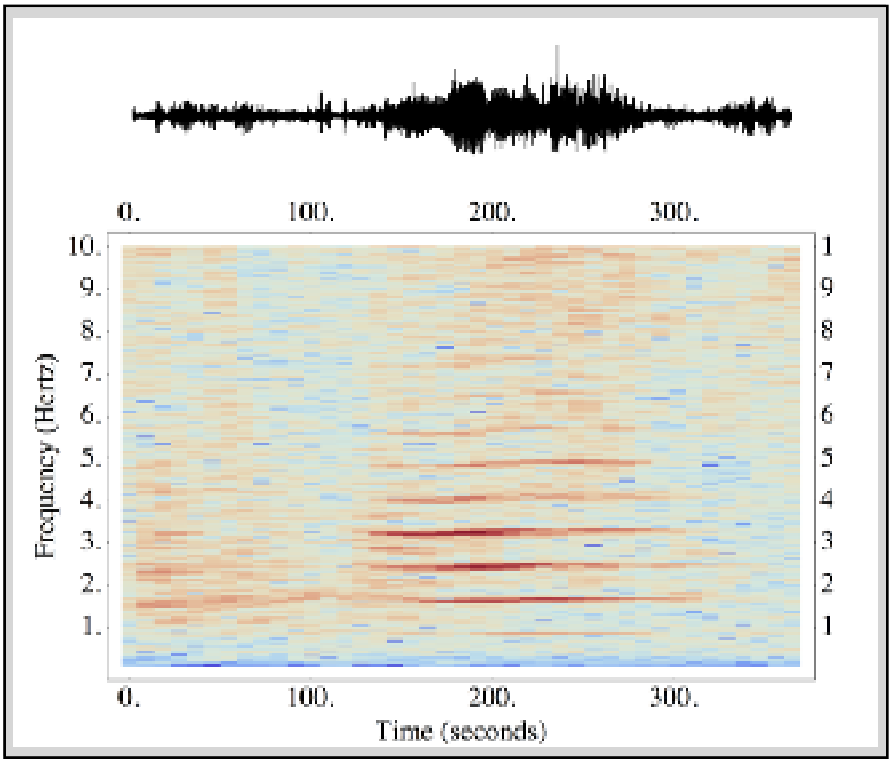

Figure 2.10. Seismogram (top panel) and spectrogram (lower panel) of the tremor signal shown in Fig. 2.9. The frequency axis in the spectrogram is pointing upwards, the time axis is pointig to to the right. Red colors correspond to high intensities, blue colors to low ones. The time scale for the spectrogram is the same one as the one for the seismogram. Click on the image to hear the sound.

If we transpose this signal into the audible range, again using the principle of accelerated playback, we can clearly hear when the overtone rich part of the signal starts (click on the image in Fig. 2.10 to hear the signal).

A similar example comes from Mount Arenal in Costa Rica (Fig. 2.11). One can easiliy identify 3-4 overtones. Most interesting with respect to this signal is the fact that the fundamental and the overtones change their frequencies as a function of time. In other words, here we have a developing melody.

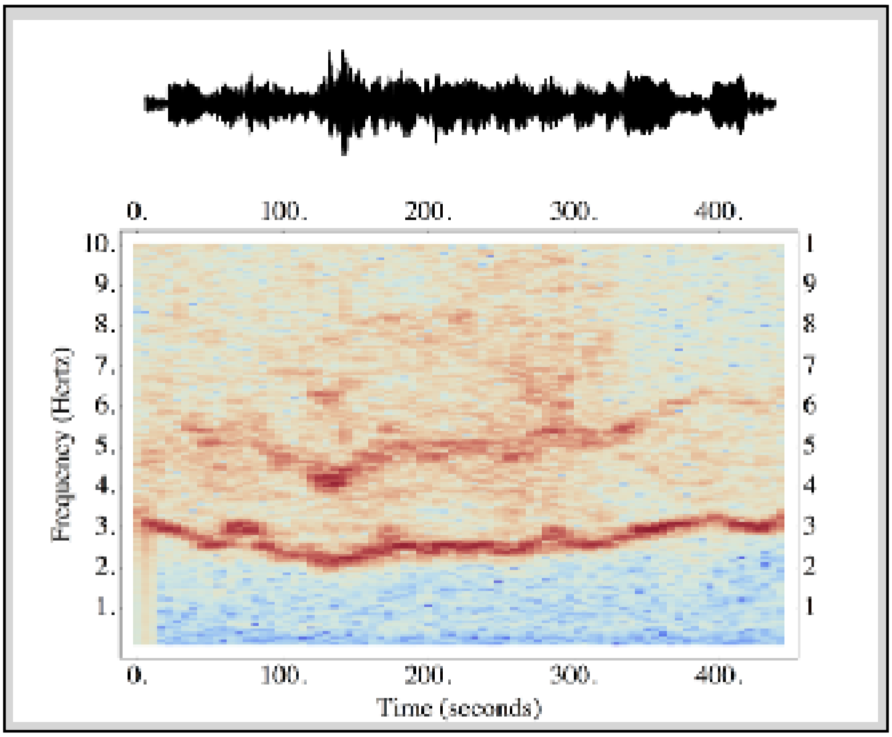

Figure 2.11. Tremor signal from Mt. Arenal in Costa Rica. Same display as in Fig. 2.10 . Click on the image to hear the signal.

In the model of the stopped pipe (cf. Fig. 1.11), this would correspond to a change in the length of the air column. Volcanoes do not only produce flute-like signals but also melodies. But even more. In 1996, Mt. Merapi (Fig. 2.13) has given a really interesting concert.

Figure 2.12. Mount Merapi in Indonesia (photo J. Wassermann). .

If you ever wondered about the origin of techno music, the answer may be given below (Fig. 2.13). The top panel shows the vertical ground motion at the seismic stations KLT which the Potsdam group of the Merapi project was operating close to the summit of Mt. Merapi in cooperation with the Volcanological Survey of Indonesia. The total length of the signal corresponds to 4.5 days. One can identify three time segments with different amplitudes. The tremor signal starts somewhere in the middle part. From each of the three segments, time windows of 2h duration were selected which are further enlarged in the bottom panels. Before the start of the tremor signal, an extremely rhythmical signal appears which accelerates towards the tremor and finally dissappears.

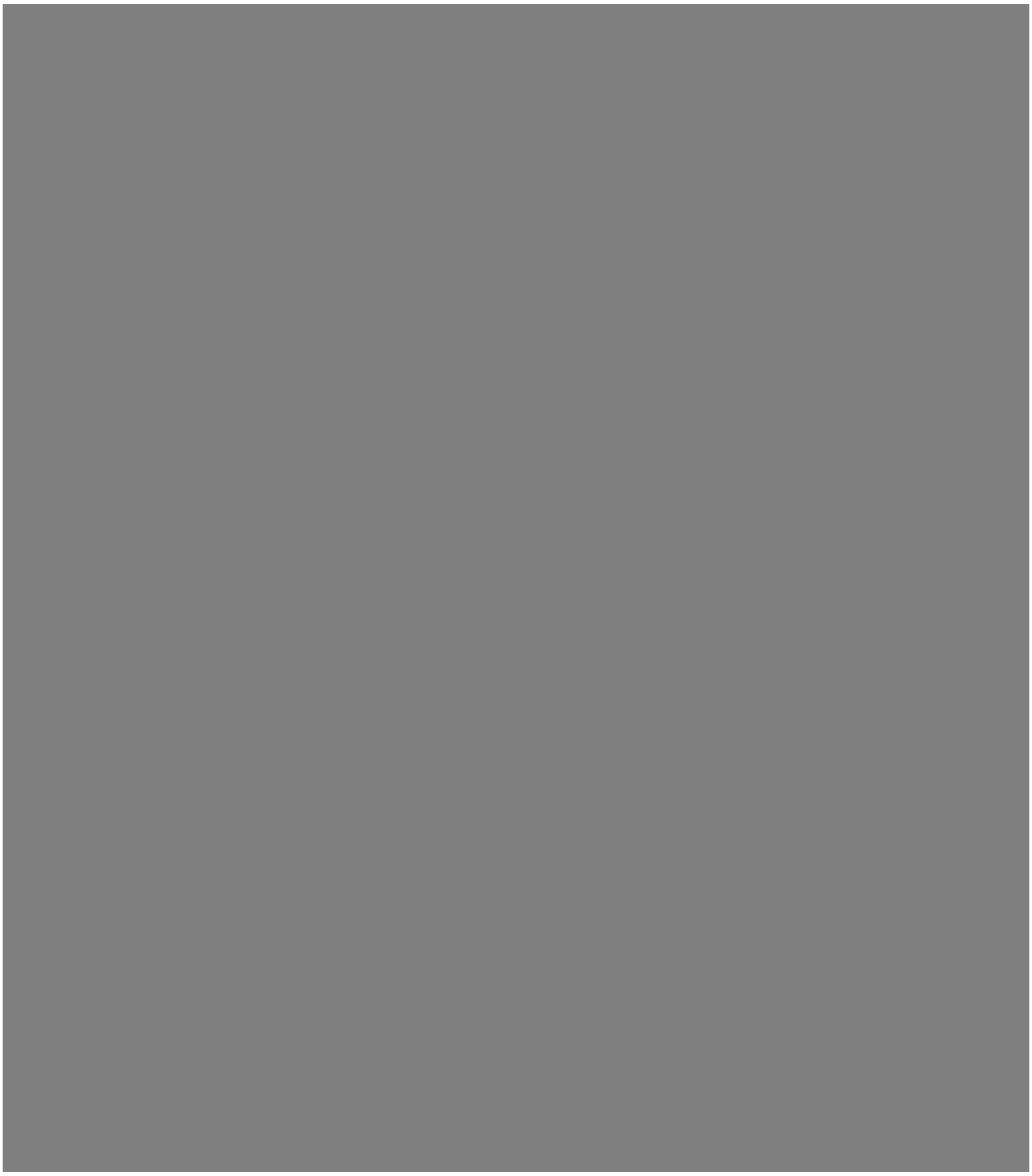

Figure 2.13. Vertical ground motion record (4.5 days) from the fall of 1996 from station KLT at Mount Merapi/Indonesia jointly operated by University of Potsdam, GeoForschungsZentrum Potsdam and Volcanological Survey of Indonesia. A volcanic tremor signal develops in the middle part. Click on the images, each of which correspond to two hour segments, to listen to the corresponding signal. Note the rhythm in segment 1, augmented by a second "player". .

A rhythmically pulsating source is another way to generate spectra which are rich in overtones as can be seen from the spectra corresponding to the selected two hour time windows from above (Fig. 2.13).

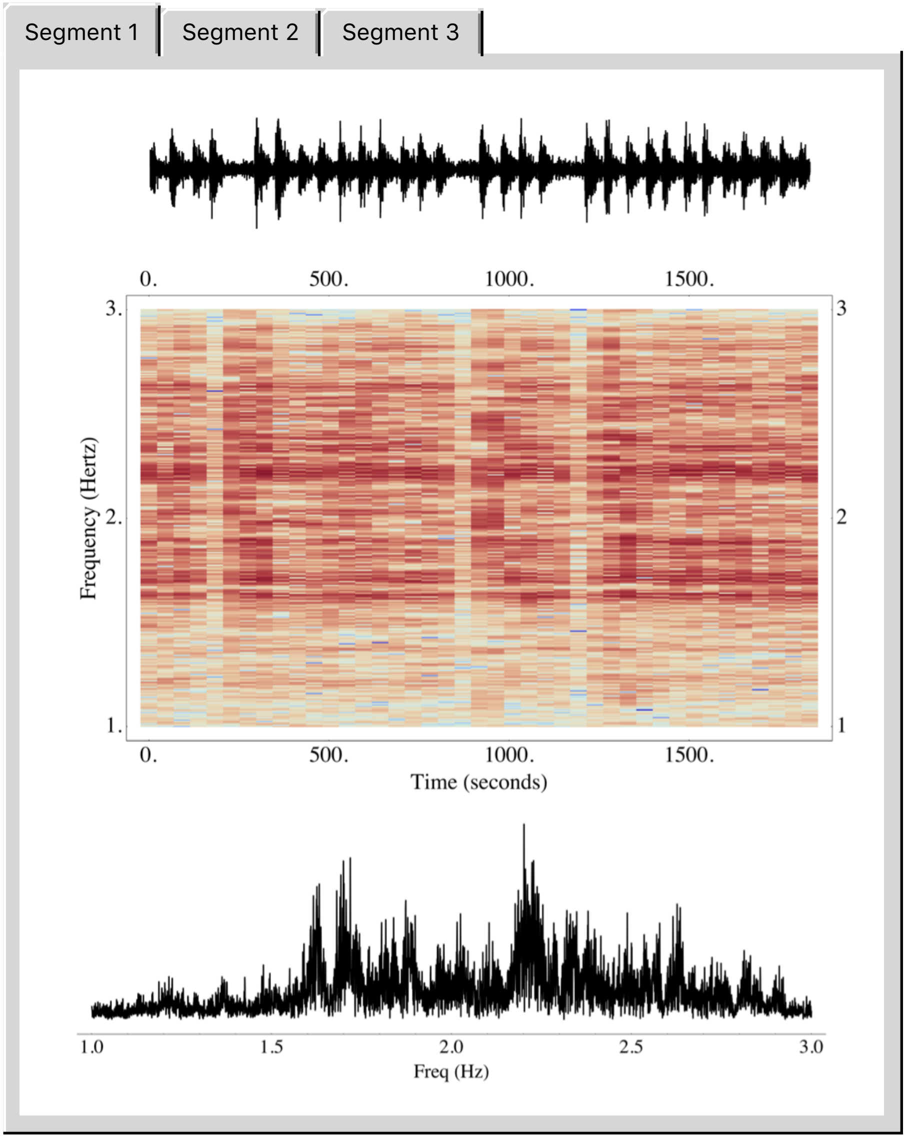

Figure 2.14. Close-up seismograms, spectrograms and spectra corresponding to 30min time windowsselected from each of the segments shown in the bottom panels of Fig. 2.13 (Wassermann, 2002).

We can clearly identify the rythm and some of the overtone in particular in the first two segmentss. The spectra are not completely harmonic, though. They would be, however, if the time intervals between the individual pulses would be constant. In this case, we would observe a completely harmonic spectrum with an integer ratio sequence of overtones just like a whistle or flute. Instruments which use this mechanism for the generation of sound are the siren (Fig. 2.15) and the human voice (Fig. 2.16).

A siren is essentialy a disk with holes in equal distances from each other (Fig. 2.15). It is rotating in front of a jet through which air is pressed. Periodically, pressure pulses can escape so that the air pressure behind the disc is changing rhythmically. This generates the sound waves which we can hear. We will hear an a , if the siren is operating at 440 pressure pulses per second.

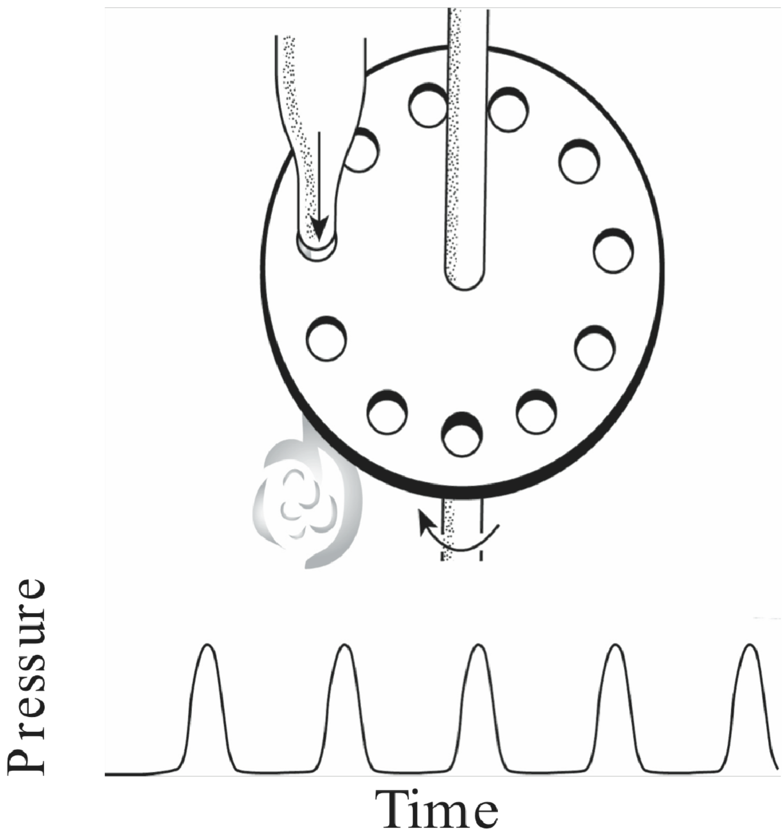

Figure 2.15. Sound generation within a siren. After Pierce (1999).

The sound generation mechanism of the human voice has some similar features. The opening and cosing of the vocal chords (Fig. 2.16) generates rythmical pressure pulses in the vocal tract which we can hear as sound. We will hear an a, if there are 440 pressure pulses per second.

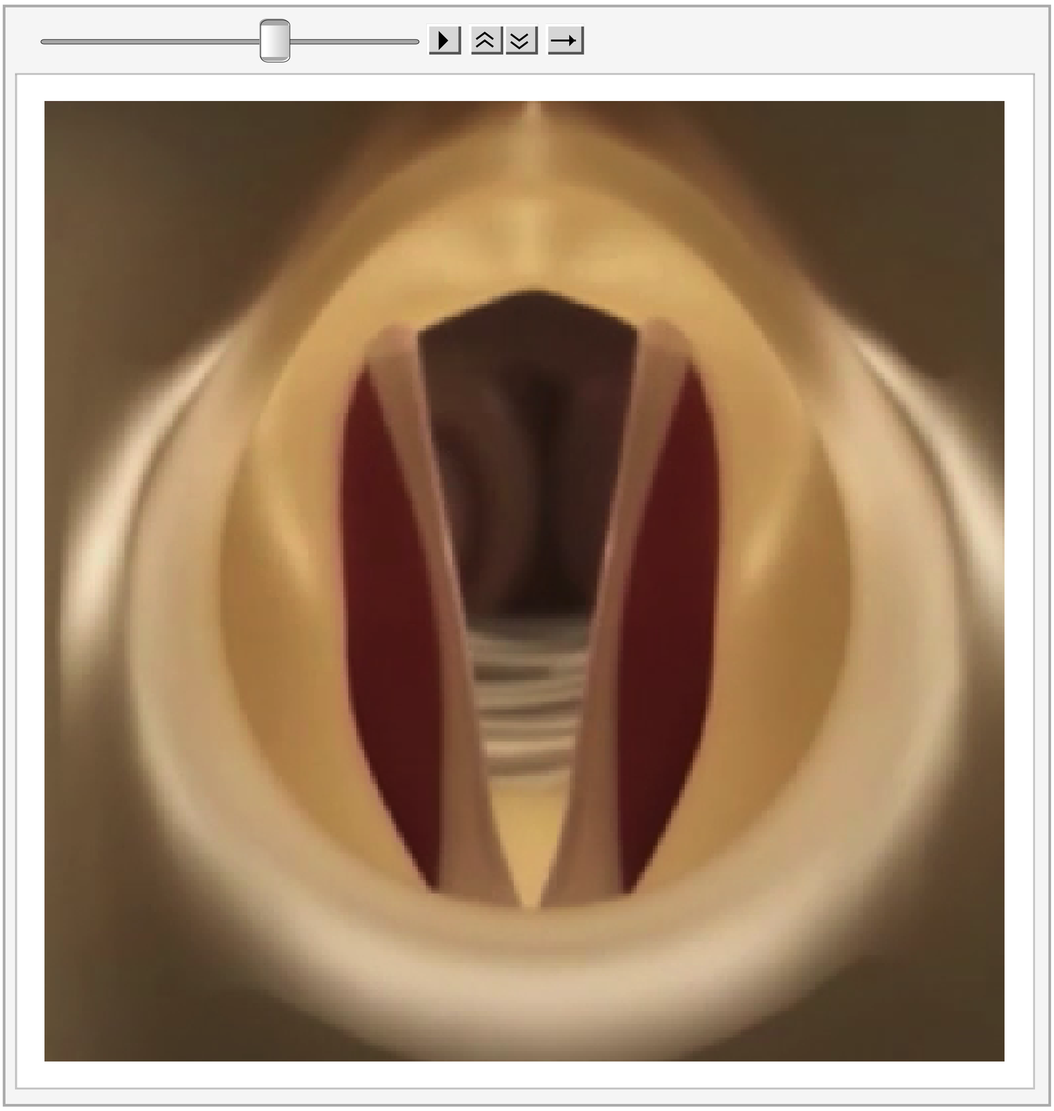

Figure 2.16. Sound generation mechanism of the human voice. The vocal chords open and closes rythmically thus generating pulsating pressure pulses in the vocal tract above. Click on the play button (▸) to start the animation. Modified from X:ENIUS “Wie funktioniert unsere Stimme” Arte, 12. Dec. 2013.

With respect to the volcano, the crucial question is which of the mechanisms discussed above actually generates the regular spectrum. This will decide about the physical meaning of melodies. Within the flute model, a change in frequency could correspond to a change of the oscillating volume, for example of the gas/magma column within the conduit. In the siren or voice model it depends on the cause of the rhythm. Most probably it would correspond to a change of the degassing speed (e. g. Hellweg, 2000; Konstantinou and Schlindwein, 2002). Getting back to acoustics, I hope I could demonstrate that soundwise volcanoes have much more to offer than earthquakes. Finally, I want to discuss an even bigger instrument: the whole Earth.

2.4. The whole Earth

As an instrument, the Earth generates sound with a pitch which is again a couple of octaves deeper than what we have considered so far. Here, we have to deal with the eigenvibrations of a sphere which are quite interesting by themselves. Depending on the type of movement, spheroidal and toroidal modes are distinguished. Spheroidal modes cause a displacement of the Earth`s surface in radial as well as in horizontal direction. Toroidal modes, on the other hand only cause a transverse displacement. As with the drums, the different modes are identified by the number of nodal surfaces. Below, you can see the movement corresponding to a few spheroidal and toroidal modes (Figs. 2.17- 2.18). The one with the lowest frequency in the Earth is the OS2 with a period of 54 min .

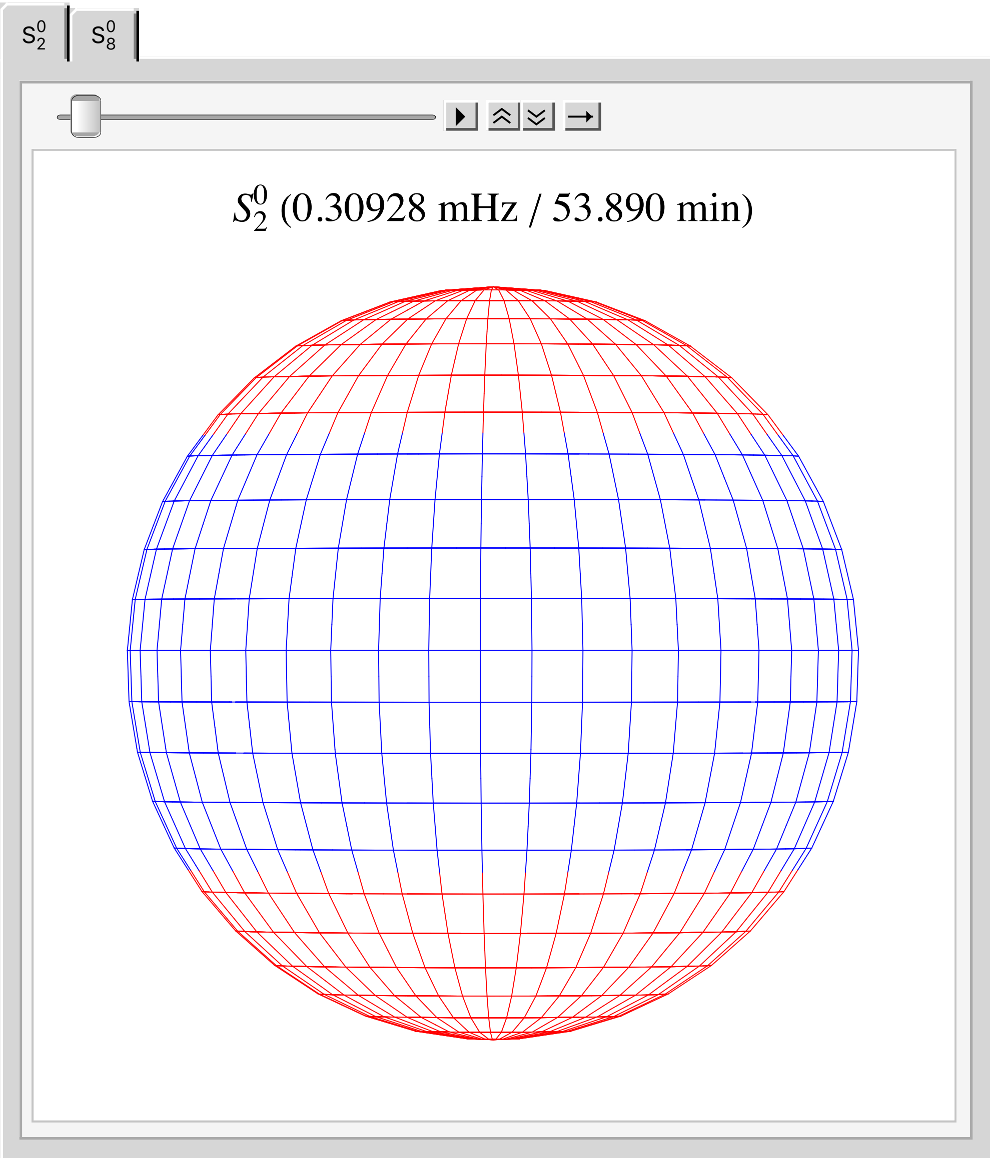

Figure 2.17. Spheroidal modes of a vibrating sphere. Select a mode and click on the play button (▸) to start the oscillation.

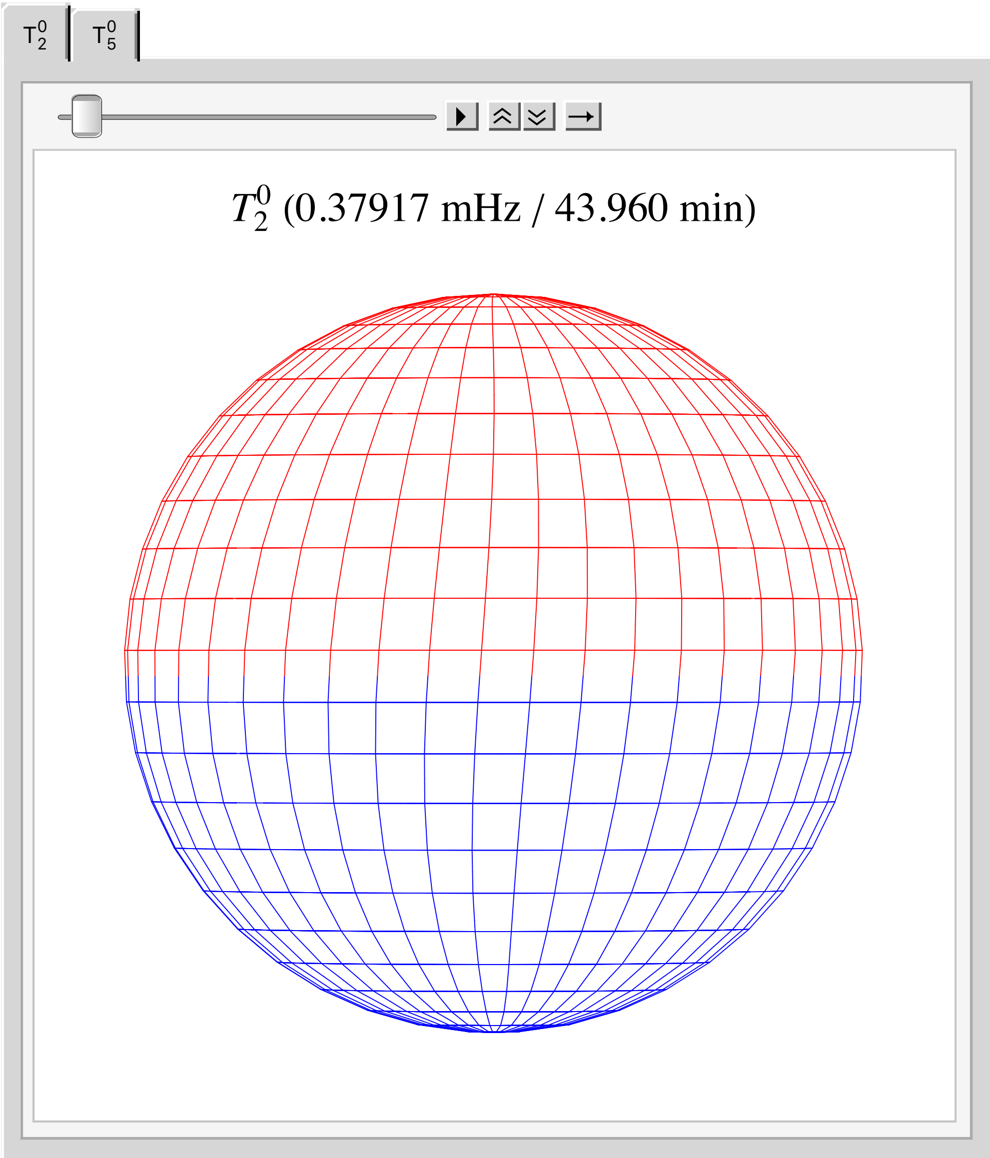

Figure 2.18. Toroidal modes of a vibrating sphere. Select a mode and click on the play button (▸) to start the oscillation.

The existence of free oscillations of the Earth was convincingly demonstrated for the first time following the Chile earthquake of May 22, 1960, one of the largest earthquake during the last century. Another earthqake which caused the whole Earth to ring for several days, was the great Bolivia earthquake of June 9, 1994 which broke the Nazca plate at a depth of roughly 640 km (Fig. 2.19).

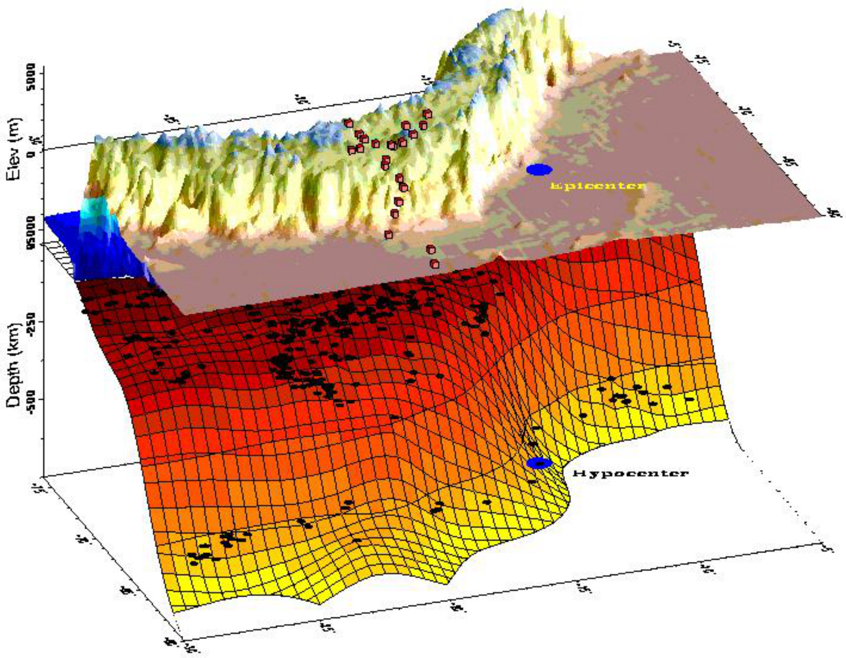

Figure 2.19. Geographical and tectonic setting of the earthquake of June 9, 1994 below Bolivia. Source: http://www.geo.arizona.edu/researchers/tinker/research/Banjo/.

The eigenvibrations generated by this earthquake were recorded at many stations all around the world. In Fig. 2.20 you see the spectrum - the sound spectrum of the whole planet - corresponding to the record obtained at the GeoForschungsZentrum Potsdam.

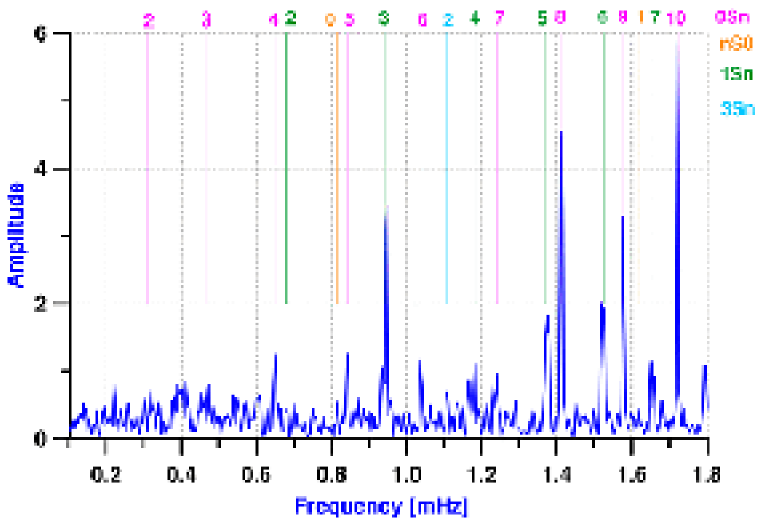

Figure 2.20. Spheroidal modes recorded after the Bolivia earthquake of Jun 9, 1994 at the GeoForschungsZentrum in Potsdam/Germany. Note that the frequencies are given in mHz (0.26 mHz corresponds to a period of roughly 1 h). Source: http://www.gfz-potsdam.de/pb1/pg3/grav/slg/free_e.html.

Figure 2.21 shows the corresponding time-frequency plot. From the bands of warm colors one can see that the Earth kept ringing for days, in several modes.

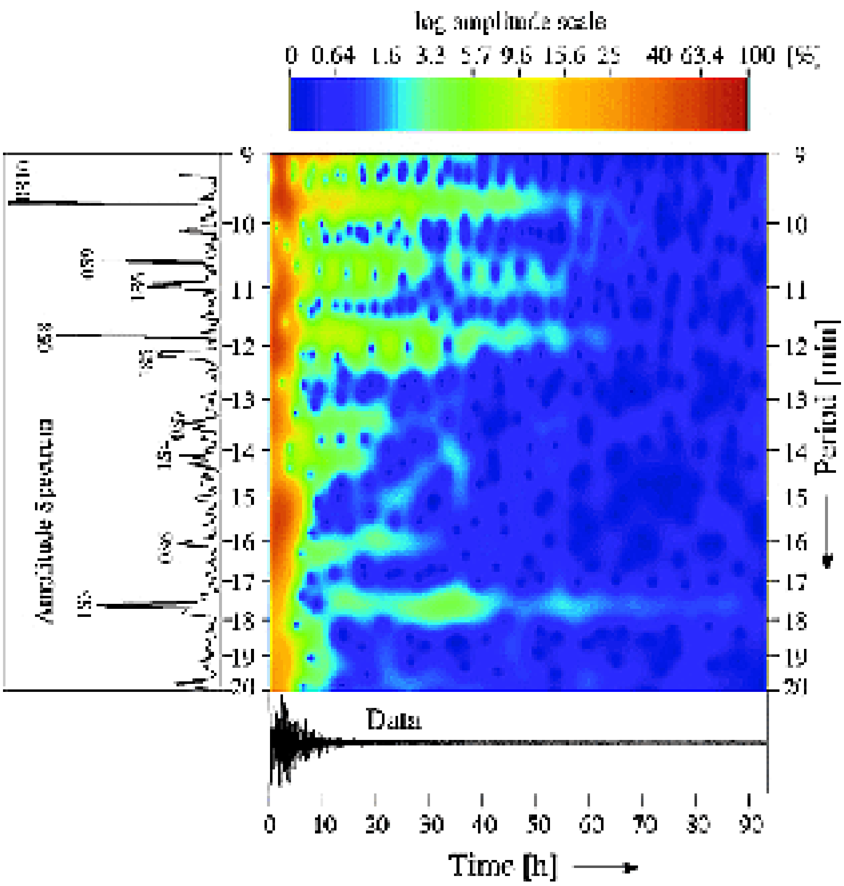

Figure 2.21. Time-frequency plot of spheroidal eigenvibrations of the Earth following the Bolivia earthquake of June 9, 1994. The time axis points to the right, the frequency axis points upwards. Source: http://www.gfz-potsdam.de/pb1/pg3/grav/slg/free_e.html.

Seismically, June 1994 was quite an active month with a total of 5 larger events which were all recorderd globally. The record below (Fig. 2.22) from the Black Forest Observatory in southern Germany (BFO) shows 21 days of vertical ground motion recordings containing all of these events. Click on the image to listen to this record - transposed according to the principle of accelerated playback again.

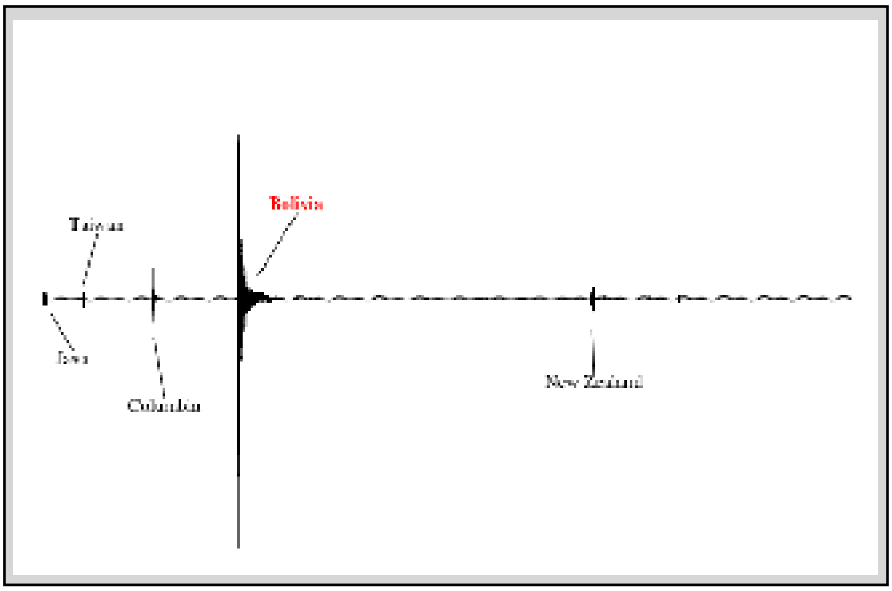

Figure 2.22. Vertical ground motion record during June 1994 at the seismic station BFO in southern Germany. The larger oscillations correspond to earthquakes in Java, Taiwan, Columbia, Bolivia (the biggest one), and New Zealand. Click on the start of the player symbol to hear the ringing after the Bolivia earthquake, however, transposed by 17 octaves. The onset of each earthquake is audible as a beat. One can hear very clearly how the Earth kept ringing after the Bolivia earthquake.

Up to a few years ago, it was thought that the free oscillations of the whole Earth were only excited by large earthquakes. Until in 1997, Naoki Suda and Kazunari Nada demonstrated that eigenvibrations of the Earth could also be observed at times without large earthquakes.

Subsequently, Ruedi Widmer-Schnidrig from the black forest observatory has shown that this “hum” can also be observed at seismic stations of the German Regional Seismic Network (Fig. 2.23).

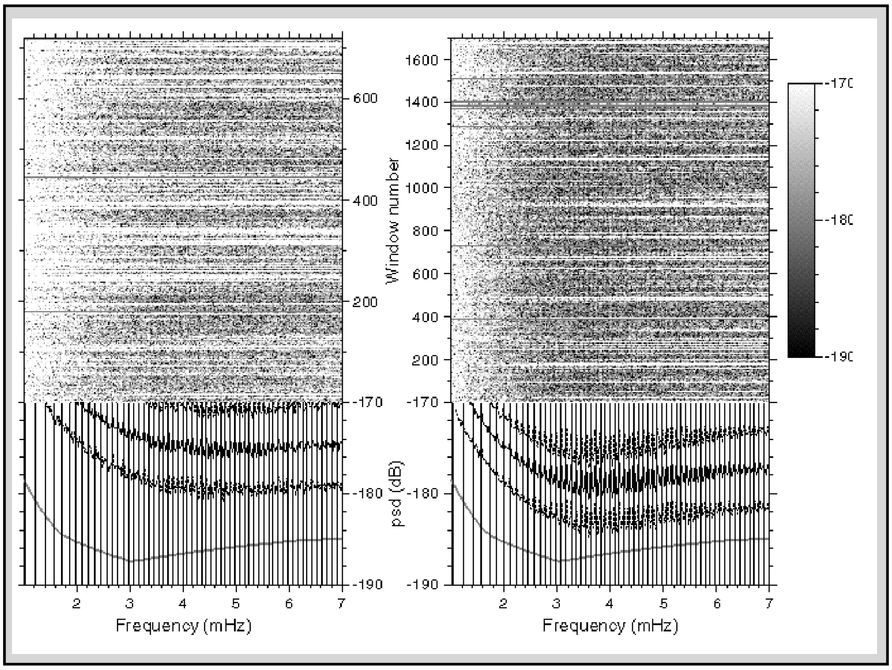

Figure 2.23. Vertical ground motion spectra calculated from reords obtained at the black forest observatory (BFO) and a station on the island of Rügen (RGN). The vertical lines correspond to the spectral lines making up the hum. Plots courtesy of R. Widmer-Schnidrig. In order to generate an acoustic impression of how the hum might sound if we could hear it, all modes contributing to the hum (OS12 - OS65 corresponding to 2-7 mHz) were superimposed assuming them to be uncorrelated. Click on the image to hear these (synthetic) signals (transposed by 17 octaves).

It is believed that the hum is generated from interaction of the whole Earth with the atmosphere. It is hard to say how the hum would sound if we could hear it. Recorded hum signals are dominated by so much background noise that it is hard to isolate it technically. For that reason I have generated synthetic hum signals which can be heard by clicking on the image in Fig. 2.23.

2.5. Conclusions

We have now come to the end of our unusual journey through the soundscape of the Earth. Although I focussed on seismological/acoustical aspects, I hope it has become obvious what a fascinating musical instrument we are living on but also what temptations it might create for a modern composer to work with those sounds. To close this loop, you can now hear the first few tunes of Inner Earth, a seismosonic symphony, composed by Wolfgang Loos, in which he has also used some of the sound examples which I have been presenting above.

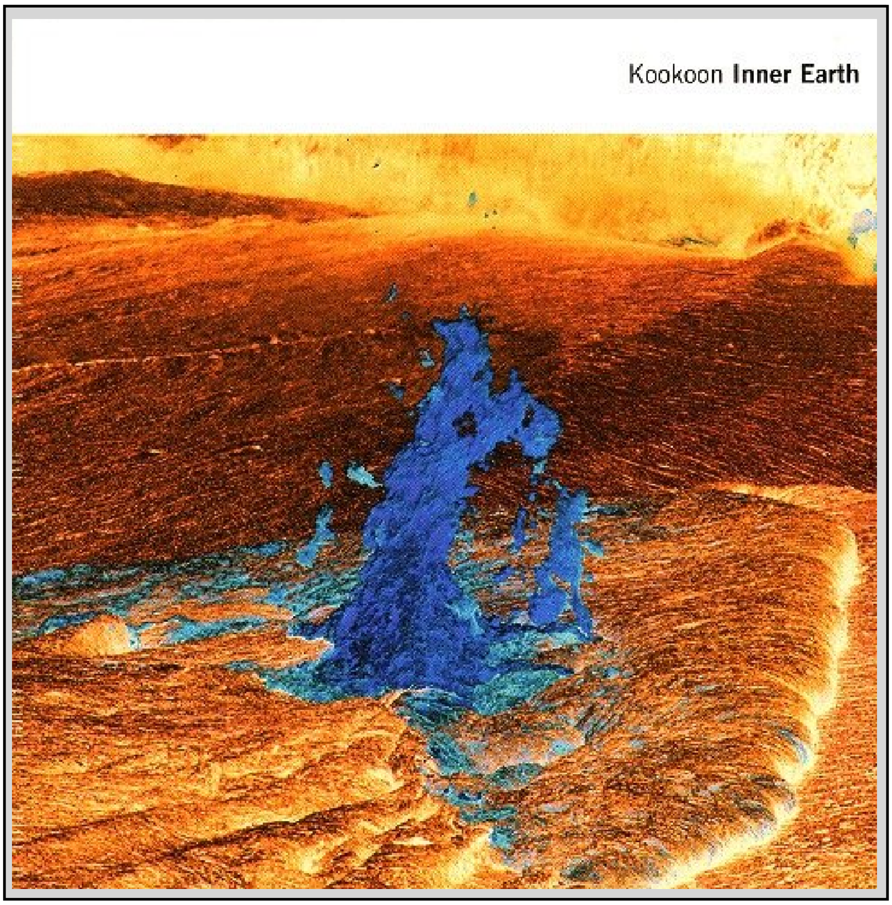

Figure 2.24. Inner Earth, a seismosonic symphony (Traumton records). Seismic signals from earthquakes and of volcanic origin were transformed, modified and recomposed. Click on the image to hear the beginning of the first movement.

I hope I could demonstrate the relationship between earthquakes and percussion instruments, and what flute, the human voice and sirens have in common with volcanoes. In this spirit, I want to conclude in a single sentence:

The fault beats, the volcano whistles and sings and the Earth rings and hums and hums and hums......

Acknowledgments and references

My work on the interfaces of seismology, the physics of vibrations, and music has been stimulated by many people who have contributed with material, suggestions and inspirations. I owe sincere thanks to (in alphabetical order of last names):

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Related links

Sounds of Seismic - Earth System Soundscape : http://sos.allshookup.org

IEI - Inner Earth Interpreter: http://i-e-i.wikispaces.com/home