COLLABORATIVE STUDY OF INTERACTIVE SEISMIC ARRAY SONIFICATION FOR DATA EXPLORATION AND PUBLIC OUTREACH ACTIVITIES

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ABSTRACT

Earthquakes are studied on the basis of seismograms. When seismologists review seismograms, they plot them on a screen or paper after preprocessing. Proper visualisations help them determine the nature of earthquake source processes and/or the effects of underground structures through which the seismic wave propagates. Audification is another method to obtain an overview of seismic records. Since the frequency of seismic records is generally too low to be audible, the audification playback rate needs to be increased to shift frequencies into the audible range. This method often renders the playback of sound too fast to perceive the nature of earthquake rupture and seismic propagation. Furthermore, audified sounds are often perceived as fearful and hence unsuitable for distribution to the public. Hence, we aim to understand spatio-temporal wave propagation by sonifying data from a seismic array and to design a pleasant sound for public outreach. In this research, a sonification researcher, a composer and a seismologist collaborated to propose an interactive sonification system for seismologists. An interactive sonification method for multiple seismic waves was developed for data exploration. To investigate the method, it was applied to a seismic array of the wave propagation from the 2011 Tohoku-oki earthquake over Japanese islands. As the playback rate is only 10 times in the investigation, it is easy to understand the propagation of seismic waves. The sonified sound shapes show some characteristics and distributions such that seismologists can easily determine the time span and frequency band to be focused on. The case study showed how a seismologist explored the data with visualisation and sonification and how he discovered triggered earthquake by using the sonified sound.

1. INTRODUCTION

Earthquakes are energetic natural events in the Earth and huge earthquakes cause disasters in many ways, such as seismic shaking, surface rupture, and tsunami. Because of the impact of huge earthquakes on society, studies on earthquake phenomena, seismic hazard, and disaster prevention as well as public outreach activities are quite important. Seismologists usually analyse seismograms[1] to extract information including seismic source processes. The seismograms also represent the shaking felt by people. Therefore, seismograms must be useful for both research and public outreach activities.

When seismologists review seismograms, they usually plot them on a screen or paper after preprocessing. Proper visualisations help them determine the nature of earthquake source processes and/or the effects of underground structures through which the seismic wave propagates. Based on such observations, the seismologists design data analyses to extract the findings objectively and quantitatively.

Audification is another method to obtain an overview of the seismic records [1]. Many seismic waveforms have been audified by seismologists and artists [2, 3, 4, 5]. Since the frequencies of seismic records are generally too low to be audible, the audification playback rate needs to be increased to shift frequencies into the audible range. However, this often renders the playback of sound too fast to perceive the nature of earthquake rupture and seismic propagation. Although the fearful sounds of such audification is reminiscent of the threat of earthquakes, it hampers the objective understanding of earthquake phenomena.

Sonification is another way to represent seismic waves, and various methods have been investigated by sonification researchers and composers [6, 7, 8]. Since sonified sounds have more variety compared to audified sounds, seismic sonification is used for not only musical works, but also for public outreach activities and data explorations.

The problem in interdisciplinary sonification research, as Goudarzi pointed out [9], is that sonification researchers often know little about seismology and the seismologists are not familiar with sonification methodology. Nevertheless, some of the interdisciplinary sonification studies succeeded in contributing to the domain of science [10, 11, 12]. For seismologists to use sonification, it is necessary to focus on the issues significant to seismology. Therefore, it is beneficial to distribute sonification tools and to describe the advantages of the sonification over traditional visualization in seismology.

In this study, we adopt an interdisciplinary design process [9], namely a sonification researcher, a composer, and a seismologist collaborate to propose an interactive sonification method for seismologists. The benefits of collaborative study are as follows. (1) We can focus on significant seismological problems or data. Collaboration with a seismologist can prevent the sonification researcher from processing the data inappropriately. (2) We can adapt sonified sound for the domain requirements. Collaboration with a composer can make sound easier to understand naturally based on music theory.

We aim to understand spatio-temporal wave propagation by sonifying data from seismic array and to design a pleasant, sound for public outreach. Since seismic waves from neighbouring stations are correlated, we use the audio gestalt strategy [13] for the sonification method. Thus, we can hear similar waves in the same stream to recognize salient unexpected events easily when they occur.

[1] Records produced by seismographs at seismic stations.

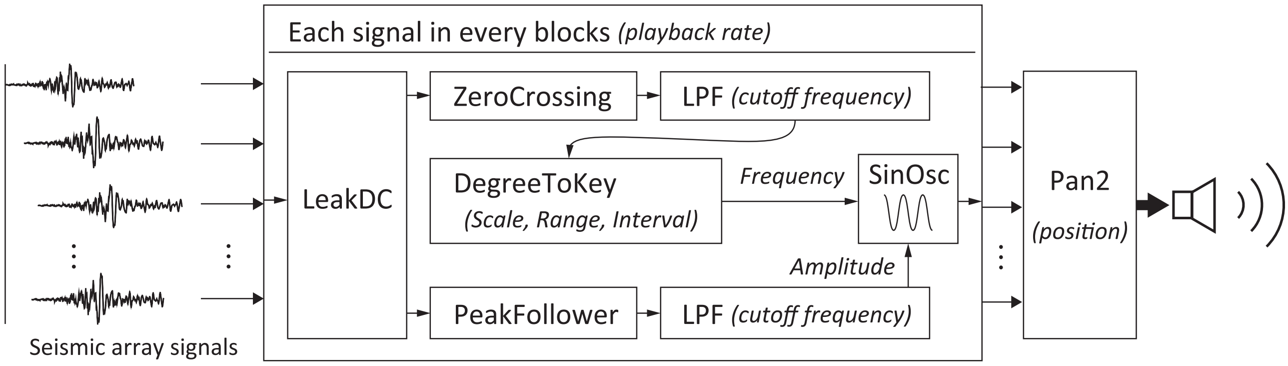

Figure 1. Flow of seismic datafor sonification. Each box represents common functions of SuperCollider, and italic words represent parameter variables.

2. METHOD

We implemented audification and sonification designs for a seismic array to achieve the primary aims of our collaboration, which are to understand seismic wave propagation by sonifying data from multiple stations, and to design a possible pleasant sound for public outreach. The sonification method was built with common functions of SuperCollider. We also implemented custom classes that provide functions to parse the seismic data, to perform simple signal processing tasks such as DC removal and normalization, and to audify seismic data both in real-time and non-real-time (rendering to a disk as fast as possible).

2.1 Audification and Sonification Method

As an example, we have chosen to use the data from the 2011 Tohoku-oki, Japan earthquake for designing the sonification. The famous sonification of the seismic array in the Tohoku-oki earthquake is available on YouTube [14], and its playback rate is greater than 1000 because the target span is a few days from earthquake occurrence and they presented the aftershock activity. In this study, we focused on seismic propagation from the mainshock; therefore, the target duration was 5 min. starting from onset of the mainshock. Seismologists require a maximum duration of approximately 1 min. Therefore, we have to design a playback rate less than 10.

2.1.1. Audification of Seismic Array

In this system, we audify seismic data from multiple stations such that the spatio-temporal wave propagation becomes audible. Figure 2 shows a SuperCollider pseudocode for audification. The locations of stations are mapped for localization within the stereophonic image. The recorded onset of each data point determines the temporal alignment of each audified event. The global temporal scale, as well as the playback rate of each seismic wave, is transposed by a factor of 10. The transposition and the consequently reduced time scale enabled us to listen to how a seismic wave propagates and to find earthquakes potentially triggered remotely.

2.1.2. Sonification of Seismic Array

Even after transposing the playback rate of each seismic wave by a factor of 10, the sound is rather rumbling and unclear. Although it is possible to transpose the seismic waves further, the global time scale of seismic wave propagation will be consequently reduced, which was not desired.

Algorithm 1 Audification of seismic array

```
seismic_array.do {|start_time id|
  Routine {
    start_time.wait;
    {
      var rate, sig, freq, peak;
      sig = PlayBuf.ar(1, ~bufs[id], rate, doneAction: 2);
      sig = LeakDC.ar(sig);
      DetectSilence.ar(sig, doneAction: 2);
      Pan2.ar(sig, id/(seismic_array.size-1)*2-1);
    }.play;
  }.play;
}
```

Figure 2. SuperCollider pseudocode for audification

Algorithm 2 Sonification of seismic array

```
seismic_array.do {|start_time id|
  Routine {
    start_time.wait;
    {
      var rate, sig, freq, peak;
      sig = PlayBuf.ar(1, ~bufs[id], rate, doneAction: 2);
      sig = LeakDC.ar(sig);
      freq = ZeroCrossing.ar(sig);
      freq = LPF.ar(freq, 100);
      freq = DegreeToKey.ar(scale.as(LocalBuf),
              freq.cpsmidi.round, 12, 1, 5).midicps;
      peak = PeakFollower.ar(sig, 0.7);
      peak = LPF.ar(peak, 1);
      sig = SinOsc.ar(freq, 0, peak);
      DetectSilence.ar(sig, doneAction: 2);
      Pan2.ar(sig, id/(seismic_array.size-1)*2-1);
    }.play;
  }.play;
}
```

Figure 3. SuperCollider pseudocode for sonification

With this sonification design, we sought to overcome the problem of intelligibility while maintaining the transposition rate. We have also addressed our aim of producing a more pleasant sound with this sonic design.

Figure 1 shows the schematic data flow and Figure 3 shows a SuperCollider pseudocode for sonification. In order to understand spatio-temporal wave propagation, we need to focus on the change of dominant frequency and amplitude envelope.

Thus, we applied zero-crossing over a moving window with the *ZeroCrossing* function and an amplitude follower with the *PeakFollower* function to derive the dominant frequency and amplitude envelope estimations in each wave. Since seismic waves generally include high-frequency components, we need to remove them with the *LPF* function to make the sound pleasant. We also used discrete frequency mapping with the *DegreeToKey* function to utilize various musical scales. Then, we synthesized parameter-mapped sinusoid wave with the *SinOsc* function and panned with the *Pan2* function according to location of seismic stations.

In contrast to audification, this sonification method enables the seismic waves to provide parameters for sound synthesis. This allows us to maintain a coherent playback rate while the dominant frequency dynamically changes. Since each seismic wave contained a similar component, the waves were formed as one large sound object based on gestalt cognition. Consequently, the sonified sounds become bubble-like timbre so that this method satisfies the aim of a "more pleasant sound."

2.2 Interface of Interactive Sonification Tool

For seismologists, we have implemented an interactive sonification system with a graphical user interface (GUI). With the GUI, users can interactively specify the geographic region, method (audification or sonification with choices of musical scales), and global time scale of sonification (Figure 4). The system intends to provide an interactive means for seismological explorations (from global spatio-temporal observation to regional selective listening) and for a real-time demonstration of outreach purpose.

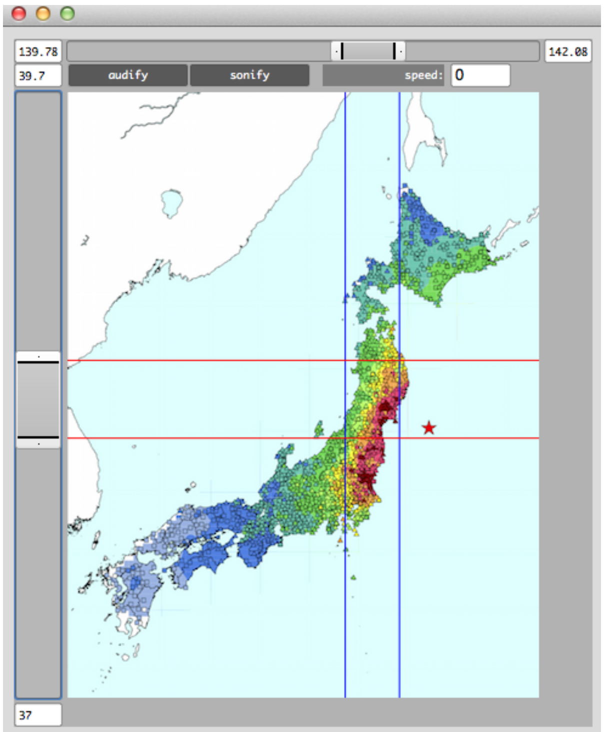

Figure 4. GUI of interactive seismic array sonification system. Users can specify the geographic region.

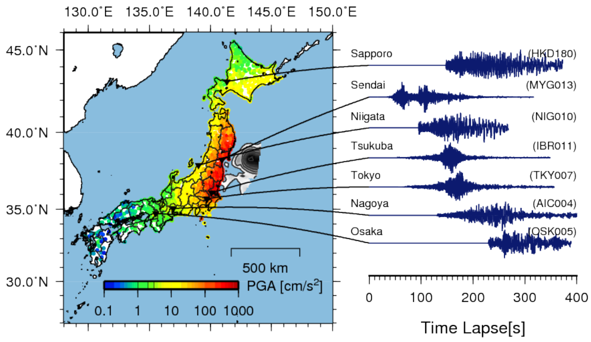

Figure 5. Peak ground accelerations (PGA) in vertical components and examples of seismic waves from the 2011 Tohoku-oki earthquake. Densely distributed symbols indicate locations of seismic stations coloured by PGA. Contours in the grey-scale image show the slip distributions of the fault inferred from seismic data [16]. The contour interval is 10 m. The seismograms displayed on the right-hand side are vertical accelerograms from K-NET stations in well-known cities.

3. CASE STUDY

In this section, we describe how the seismologist analyses and explores the seismogram data with the proposed method.

3.1 Earthquake, Data description

We first applied the sonification method to the 2011 Tohoku-oki, Japan earthquake (magnitude 9.0) that impacted the society because of the disaster caused by the strong ground shaking and the devastating tsunami that hit the Pacific coast of Japan Islands and propagated across the Pacific Ocean (Figure 5). It is worth sharing the seismic records with the public to draw people's attention to earthquake disasters and the preparedness for them.

This huge earthquake was recorded by seismometers all over the world in addition to the dense seismic networks in Japan. K-NET and KiK-net are nationwide strong-motion seismic networks composed of seismometers [15][2]. K-NET stations have instruments only on ground surface, while KiK-net have borehole and surface seismometers. We use the up-down component of acceleration recorded at the surface to observe seismic shaking often amplified by near-surface soil, as we feel on the surface. They both provide accelerations of three-dimensional ground motions. The record is started at the time when the amplitude exceeds a threshold; therefore, stations away from the earthquake source region may have missed the first arrivals of seismic waves with small amplitudes.

3.1 Nation-wide sonification

First, we sonify the seismic data from all over Japan. We had data from more than 600 stations, and we picked 116 representative stations from them evenly in space. The playback speed is 10 times the actual speed. The synthesized sound spatializes the recorded seismic waves from different

[2] K-NET and KiK-net data by NIED are available at http://www.kyoshin.bosai.go.jp/

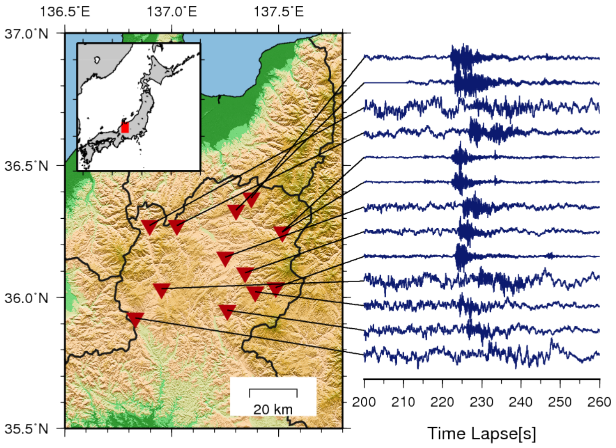

Figure 6. Seismic data in Hida area, central Japan. The inverted triangles denote the location of stations used for the areal sonification. The seismograms displayed on the right-hand side are vertical accelerograms from K-NET and KiK-net stations.

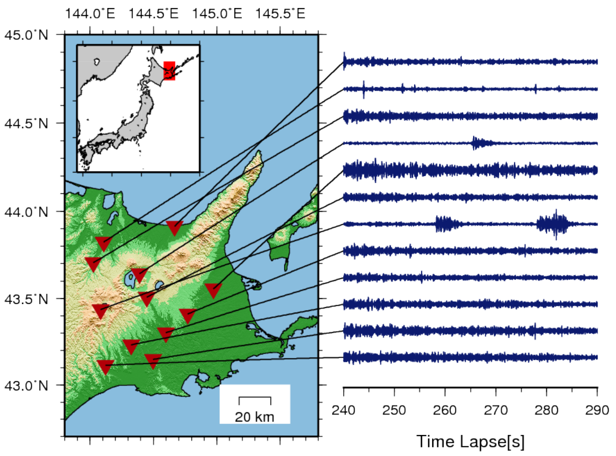

Figure 7. Seismic data in eastern Hokkaido area, nothern Japan. The inverted triangles denote the location of stations used for the regional sonification. The seismograms displayed on the right-hand side are vertical accelerograms from K-NET stations.

stations so that the overall sonic impression conveys the feeling of seismic waves propagating all over Japan. At first the sound is high-pitched and loud, and the pitch and volume become progressively lower. This reflects the elastic attenuation at a distance and anelastic attenuation especially in high-frequency waves due to scattering and absorption by the medium (i.e., underground soil and rock). It is interesting that the end of synthesized sound (around 23 s, equivalent to 230 s in the actual time after the origin time) contains a short series of high-pitched sounds, which will be investigated in the next subsection.

3.2 Regional sonification

We have explored the cause of the high-pitch sounds by sonifying seismograms from stations in particular regions. Here we show two examples that seem to be related to the high-pitched sound series. In regional cases, we sonify all stations available, while in the nationwide case, we reduced the number of stations in use.

One example is Hida area, Gifu prefecture, where a magnitude-4 earthquake was dynamically triggered by the strong seismic waves from the mainshock of the Tohoku-oki earthquake [e.g., 17]. The stations for sonification are shown in Figure 6. The sonified sound contains a high-pitched sound at the end similar to what we hear in the sound from the nationwide sonification. In fact, the timing agrees with a local earthquake seen in the seismic waveforms. Since this is recorded by nearby stations, the anelastic attenuation effect is weak and the high-frequency components in seismic waves are preserved.

Therefore, we conclude that the high-pitched sound in the nationwide sonification is due to this dynamically triggered earthquake.

Another example is east Hokkaido area. We hear some high-pitched sounds by the regional sonification using the stations shown in Figure 7. The seismograms contain high-frequency waves at one station and other waves at another station. Though it is difficult to draw conclusions from the seismic data of only one station, it is possible that the high-frequency waves originate from local earthquakes or some other phenomena that occurred near the station.

Although we can find the causes of the curious sounds by the visualisation of seismograms, the sonification makes it easy to find them.

4. DISCUSSION

Figure 8 shows a schematic of the work flow in the collaboration among a seismologist, a composer, and a sonification researcher in this study. Each node indicates a role. This schematic is quite similar to that of a conventional study [9].

From the case study, the sonified sounds satisfied the requirement, which means that the sonification design was successful. From the sonification researcher's point of view, this sonification could not succeed without the composer and seismologist. In the data exploration process, when the sonification researcher and the composer recognized the salient unexpected event, they could not interpret the meaning of the phenomenon. On the other hand the seismologist sometimes felt it difficult to listen to the auditory stream separately. When we listened to the sonified sounds together, we could notice the salient acoustic event and interpret the significance of characteristics from a seismological aspect.

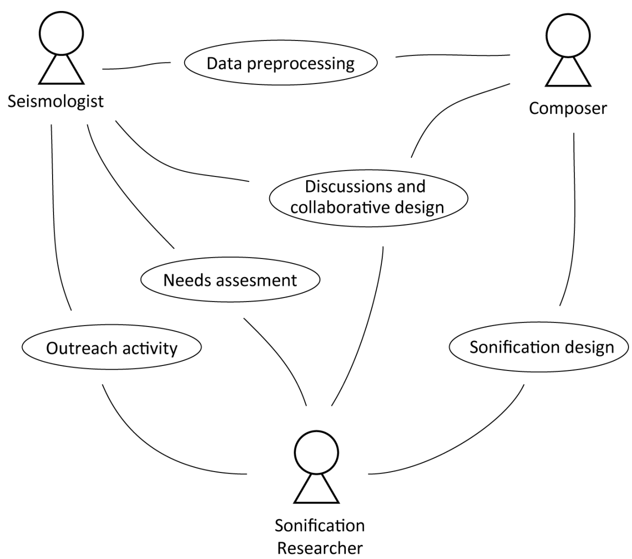

Figure 8. Schematic work flow of the collaboration.

In addition, during the use of interactive sonification tool, the seismologist could guess the seismic propagation process so that he could explore the data efficiently. If the user does not have any domain knowledge, the interactive data exploration process would be random and futile.

For public outreach activity, we presented both the visualisation and sonification simultaneously (Figure 9). Although the audience generally did not have seismological knowledge, they could recognize the high-pitched sound event. It is difficult to understand this event with only visualisation. Therefore, the sonification seemed to help the interpretation.

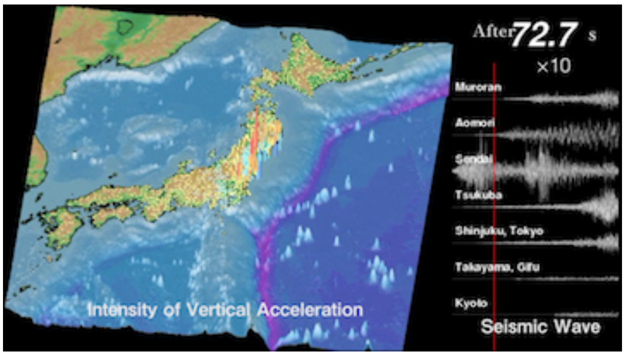

Figure 9. A snapshot of visualisation with sonification for public outreach.

5. CONCLUSION

In this paper, we proposed an interactive seismic array sonification method using collaborative design strategy. In order to design the sonification method for significant discovery in the domain, both domain knowledge and music techniques were required. We chose Tohoku-oki earthquake as an example and the sonified sound of its seismic data indicated a dynamically triggered earthquake. The sounds also satisfied the domain needs for public outreach purpose.

From the case study, we found that the interpretation of sonified sound needs not only seismological knowledge but also listening ability. From the seismologist viewpoint, the interactive system has potential for helping domain experts in the analysis of seismic propagation of a newly occurred earthquake. For future work, we will investigate how the system scaffolds domain experts' analyses and reduces their cognitive load.

6. ACKNOWLEDGMENT

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